TNO report
PML 1996-A100

Developments in missile ramjet propulsion

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Date
December 1996

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Classification
Classified by : Maj. J. Paap
Classification date : November 12, 1996
(this classification will not change)

Title	: Ongerubriceerd
Managementuittreksel	: Ongerubriceerd
Abstract	: Ongerubriceerd
Report text	: Ongerubriceerd
Annexes A - B	: Ongerubriceerd

Copy no.	: 15
No. of copies	: 29
No. of pages	: 77 (incl. annexes, excl. RDP & distribution list)
No. of annexes	: 2

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Applied Scientific Research (TNO)

Managementuittreksel

Titel	:	Developments in missile ramjet propulsion
Auteur(s)	:	Ir. R.F. Calzone
Datum	:	december 1996
Opdrachtnr.	:	A95KLu487
Rapportnr.	:	PML 1996-A100

Inleiding

De ontwikkeling van snellere wapensystemen met een grotere range houdt gelijke tred met de verbetering van missile- en vliegtuigsystemen op het gebied van detectie, identificatie en het volgen en vernietigen van doelen. Vanwege hun potentieel voor een grotere range, een langere aangedreven vlucht en de kortere tijd tot interceptie, bieden ramjets een aanzienlijk voordeel voor de voortstuwing van missiles, vergeleken met conventionele vaste-stuwstof raketmotoren.
De missile-ontwikkelingen zullen van invloed zijn op de aanschaf van toekomstige wapensystemen voor de Nederlandse krijgsmacht. Daarom heeft de Koninklijke Luchtmacht TNO verzocht om een studie uit te voeren op het gebied van ramjet-voortstuwing. Dit rapport bevat de resultaten van deze studie. Het rapport geeft een overzicht van ramjet-voortstuwing voor missiles met het oog op de technische en operationele aspecten en de huidige internationale ontwikkelingen. Tevens worden in het rapport de elementaire achtergronden met betrekking tot ramjet-voortstuwing gegeven.

Voor- en nadelen van ramjet-voortstuwing

In het rapport worden de voor- en nadelen van ramjet-voortstuwing besproken. Hierbij wordt ramjet-aandrijving vergeleken met conventionele raket-aandrijving, waarbij de levenscyclus van aanschaf (kosten), operationeel gebruik en afstoting (vernietiging) van missiles wordt gevolgd. Een samenvatting van de vergelijking tussen de verschillende ramjet-types en een conventioneel vaste-stuwstof raketsysteem is in de tabel hieronder gegeven. Bij de tabel moet worden opgemerkt dat de vergelijking in feite een kunstmatige is omdat de voor- en nadelen van een bepaald voortstuwingssysteem afhankelijk zijn van de bedoelde missie(s) en de operationele eisen.

Tabel M.1: Ramjetsystemen versus vaste stuwstof raketsystemen.

	SP ROCKET	SFRJ	LFRJ	DR
Prestatie (I_{sp})	-	++	++	+
Missie flexibiliteit	o	-	++	+
Systeem complexiteit	++	+	-	o
Systeem rijpheid	++	o	+	o
Veiligheid	o	++	-	+
Hanteren & transport	+	+	o	+
Opslag	+	++	-	+
Onderhoud	+	++	-	+
Levensduur	+	++	++	+
Milieu aspecten	-	++	++	o

SP	Solid Propellant	-	Ongunstig
SFRJ	Solid Fuel RamJet	o	Neutraal
LFRJ	Liquid Fuel RamJet	+	Goed
DR	Ducted Rocket	++	Zeer goed

Huidige ontwikkelingen

De internationale ontwikkelingen op het gebied van ramjets (in Europa, de Verenigde Staten en de voormalige Soviet Unie) worden in het rapport behandeld voor elk van de volgende toepassingen:

- air-launched standoff missiles;
- air-to-air missiles;
- air defence missiles;
- anti-radar missiles;
- anti-ship missiles.

De moderne air-launched standoff missiles zijn ontwikkeld om autonome, onbemande snelle precisie-missies mogelijk te maken. Deze systemen maken gebruik van een Turbojet of een Liquid Fuel Ramjet motor. Voor korte-afstand air-to-air missiles worden voornamelijk vaste-stuwstof raketmotoren gebruikt. Voor middenlange-afstand en lange-afstand toepassingen zijn ontwikkelingen naar ramjet-aandrijving gaande, waarbij voor de bekende toepassingen gebruik wordt gemaakt van een Ducted Rocket motor. De meeste moderne korte-afstand en middenlange-afstand luchtafweersystemen maken gebruik van een raketmotor. Een oudere korte-afstand applicatie (de SA-6) maakte gebruik van een Ducted Rocket systeem. In lange-afstand luchtafweersystemen zijn ook Liquid Fuel Ramjet motoren gebruikt. Voor anti-radar missiles (bijvoorbeeld AWACS-achtige doelen), zijn ontwikkelingen naar ramjet-voortstuwing bekend. Voor anti-ship missiles wordt een ontwikkeling naar langere afstanden waargenomen waarbij met name (Liquid Fuel-) Ramjet motoren of Turbojets gebruikt worden.

De missile-systeeminformatie die verzameld is gedurende de studie is eenvoudig toegankelijk in de bijgevoegde data base (Annex A).

Toekomstige ontwikkelingen

De praktische toepassing voor missile (ramjet) systemen zijn tot nu toe beperkt gebleven tot ramjets met vliegsnelheden rond Mach 3. De logische volgende stap voor de voortstuwing van missiles is de ontwikkeling naar hypersone snelheden (M > 5-6). Laat waargenomen doelen of erg snelle, en nog ver verwijderde, dreigingen kunnen met groter succes worden onderschept met deze snelle missiles. Hypersone voortstuwing voor missiles wordt uitvoerig bestudeerd in verschillende landen, o.a. in Frankrijk, de Verenigde Staten en de voormalige Soviet Unie. Vergeleken met het supersone vluchtregime brengt het hypersone vluchtregime speciale problemen met zich mee, die gerelateerd zijn aan de hoge snelheid. Voorbeelden van deze problemen zijn de missile-geleiding en -besturing, aerodynamische verhitting en de warhead fragment richting.

Geïdentificeerde lacunes in kennis

De volgende onderzoeksgebieden zijn geïdentificeerd als, op dit moment, nog onvoldoende bekend:

- onderhoud en levensduur van ramjet missile systemen;
- milieuaspecten gerelateerd aan ramjet missile systemen.

Vervolgstudies op deze gebieden zullen worden gedefinieerd in overleg met de Koninklijke Luchtmacht.

Contents

Abbreviations

AA	Anti Aircraft
AAM	Air-to-Air Missile
AP	Ammonium Perchlorate
AS	Air-to-Surface
ATM	Anti Tactical Missile
BVR	Beyond Visual Range
CIC	Close In Combat
CTPB	Carboxyl Terminated PolyButadiene
DR	Ducted Rocket
ECM	Electronic Counter Measures
ECCM	Electronic Counter Counter Measures
EW	Electronic Warfare
GPS	Global Positioning System
HTPB	Hydroxyl Terminated PolyButadiene
IFF	Identification Friend or Foe
IM	Insensitive Munitions
IRR	Integral Rocket Ramjet
LFRJ	Liquid Fuel RamJet
PB	PolyButadiene
SAM	Surface-to-Air Missile
SFRJ	Solid Fuel RamJet
SS	Ship-to-Ship
TDR	Turn-Down Ratio
UAV	Unmanned Areal Vehicle
VFDR	Variable Flow Ducted Rocket

Symbols

I_{sp}	Specific Impulse: thrust impulse per unit of propellant (or fuel) weight	[m/s]
M	Mach Number: flight speed is M times the speed of sound	[-]

1 Introduction

1.1 Objective

The maturation of missile/aircraft capabilities for detection, identification, targeting and destruction of targets has driven the need for weapons and weapons systems with increased speed and range. Due to their potential of extended range, longer powered flight and shorter time-to-target, compared to conventional solid propellant rockets, ramjets offer considerable advantages for missile propulsion. The advantage of long range has been widely recognized but was in fact ahead of the development of reliable long-range guidance concepts. Despite this fact, ramjet propulsion has been applied in missiles ever since the 1960s. Examples are the Russian SA-4 'Ganef' and SA-6 'Gainful' anti-aircraft missiles, the latter of which is still operational and used by many countries like the former Yugoslavia, Libya and Syria. It is believed that the new generation of guidance systems are apt to fulfil the long promised Beyond Visual Range (BVR) capability of modern missile systems, thereby taking full advantage of the virtues of ramjet propulsion. In addition, the Persian Gulf War and the war in Bosnia have stimulated the demand for long-range stand-off and air-to-ground missiles, since losses of air crews in disputes where there is no direct threat to the own country are no longer acceptable. New developments in missile propulsion indeed show that trends tend towards ramjet propulsion for medium-range and long-range missiles.

The current international developments will undoubtedly have an impact on the acquisition of future weapon systems of the Netherlands Armed Forces. It is the objective of this work to provide the information that is necessary for evaluation of these systems. The technical/operational aspects will be addressed as well as the international developments on missile ramjet propulsion. A second objective is to identify possible lacks of essential knowledge.

1.2 Historical overview

The concept of ramjet propulsion goes back to France early this century, when René Lorin (1877-1933) had the idea of using atmospheric air that is compressed in an inlet for the combustion of fuel and expanding the high-pressure, high temperature mixture in a nozzle to obtain the necessary propulsive impulse. Lorin described the principles of a ramjet in a publication in 1913 [1]. It was René Leduc (1898-1968) who developed the idea into a working concept and demonstrated it in an experimental set-up in 1934. This success lead to a registered state-mark (number 407/7) permitting Leduc to realize the first ramjet-powered airplane 'Avion Thermopropulsé': the Leduc 010 (see Figure A.1). It was only after World

War II that he was able to finish his airplane and the Leduc 010 was ready for flight in 1946. With a later version of the aircraft, the Leduc 022, near sonic speeds (Mach 1) were reached in 1957 for a short instant.

Meanwhile, the ramjet technology caught the attention of weapon system engineers, and several types of ramjet-propelled bombs and missiles were flight tested in France between 1950 and 1967. A flying bomb with a weight of 135 kg and a range of 100 km, using a solid rocket strap-on booster, was first flight tested in 1950. Soon, series production of these flying bombs started for the French army. The developments were towards higher speeds for anti-aircraft and anti-missile applications and, in 1957, the French SE-4400 attained a speed of Mach 3.7, which was probably the fastest vehicle at that time. The SE-4400 had a range of 40 km.

Also in other countries, like the US, the former USSR and the UK, ramjet propulsion research lead to new missile systems. Examples of early operational systems are the US Plover (1952), Bomarc (1952) and Talos (1958), the Russian SA-4 'Ganef' (1964) and SA-6 'Gainful' (1970) and the UK 'Bloodhound' (1952) and 'Sea-Dart' (1965). All systems are medium/long-range SAMs.

Figure A.2 shows the historical evolution of booster/ramjet concepts. The rocket engine is used to boost up the missile to speeds where the ramjet may be operated. Transition takes place at Mach numbers between 1 and 2. Three major configurations may be distinguished.

- The parallel configuration. This configuration forms the first generation of air-breathing missiles. Examples are the Bomarc (USA), the Bloodhound (UK) and the Sirius (F). The missiles consist of a solid rocket motor, with parallel ramjet motors. The main disadvantage of this concept results from the fact that the booster motor has to be carried along during the ramjet phase. This results in reduced ranges and reduced acceleration compared to a pure ramjet. For given missile mass, this also means a reduction in payload. In addition, the missile is heavy and bulky and the frontal area is large, resulting in considerable drag compared to the tandem and integral configurations, described next.
- The tandem configuration. This configuration forms the first integration attempt. Examples are the Talos (USA), the Sea-Dart (UK), the SA-4 (USSR), the Vega (F) and the Stataltex (F). The booster and ramjet motor are positioned in line with each other. The booster motor is jettisoned after operation. The intake is integrated in the vehicle and placed in the nose. In this way, the disadvantage of an unwanted high structural weight during the ramjet phase is largely overcome. However, boost and ramjet phases still have separate combustion chambers. This leads to the logical next step of applying the integral configuration.
- The Integral Rocket Ramjet (IRR) configuration is most favourable from a structural weight point of view. Examples are the SA-6 Gainful (USSR), the ASMP (F) and the A3M and S22XR propositions for FMRAAM (UK). The booster and ramjet combustion chamber are combined, which leads to an opti-

mized use of the missile structure. This concept results in the largest obtainable range and payload for a given missile size and weight. The IRR arrangement is widely used in modern ramjet-propelled missile systems.

1.3 Types of ramjet

The following ramjet types are considered. They are compared with the conventional solid propellant rocket motor in Figure A.3:
- Solid Fuel RamJet (SFRJ);
- Liquid Fuel RamJet (LFRJ);
- Ducted Rocket (DR).

The most simple type of ramjet is the Solid Fuel Ramjet (SFRJ). The solid fuel is stored in the ramjet combustion chamber and burns with the incoming air that is slowed down in the inlet(s) to gain a high static pressure and temperature. The combustion process provides the heat to vaporize the fuel so that it can mix and burn with the air. The highest values of specific impulse are obtained for this type of ramjet and for the Liquid Fuel Ramjet (see below) due to the absence of any oxidizer in the solid fuel. The advantage of this type of ramjet is its intrinsic safety due to the inert fuel (binder with additives) and the low system complexity. A disadvantage of this type of ramjet is that the fuel occupies part of the ram-combustor volume, which leads to a low volumetric loading due to the necessary inner bore. Solid fuel ramjets do not allow for simple throttling, because the fuel mass flow rate depends on local combustion chamber conditions. The solid fuel ramjet may be applied in large, long-range missile systems but also in projectiles like anti-tank or air defence ammunitions.

The Liquid Fuel RamJet (LFRJ) incorporates a tank with liquid fuel, which is pumped to the injectors in the combustor where the fuel spray is mixed and burnt with the incoming air. Due to the necessity of fuel control and pumping devices, the liquid fuel ramjet is much more complex than the solid fuel ramjet and the conventional solid propellant rocket. A disadvantage arises from the fact that, in general, the density of liquid fuels is low, 0.8 kg/m^3 for common kerosene, which is roughly a factor 2 lower than for a conventional solid propellant. This will lead to increased volume and system weight. This may be partly overcome by applying so-called slurry fuel for which higher densities are obtained by adding solid (metal) particles. Due to the thixotropic nature of the slurry (gel/solid transition), practical values of the density are limited to hardly higher than 1.0, however. Other typical problems that may occur with liquid fuels are due to their high viscosity (mainly at low temperatures), which affects pumping, ignition, combustion and heat transfer [2], see also Sections 2.3 and 2.5. The advantage of the LFRJ is that the fuel flow rate can be regulated to fulfil a wide range of missions. Therefore it offers interesting possibilities, but mainly for large systems, like long-range air-to-

ground and ground-to-ground missiles [3, 4, 5]. Finally, it should be mentioned that of all ramjet systems, the LFRJ is the most mature one.

The Ducted Rocket (DR) combines the advantages of rocket and ramjet propulsion. A solid propellant is stored in the gas generator combustor where it is precombusted to provide a fuel-rich gas to the ramjet combustion chamber. These fuel-rich gases are further combusted with the incoming inlet air. The solid gas generator propellant contains a small amount of oxidizer in order to sustain its own combustion process. Therefore, specific impulses are lower than for solid or liquid fuel ramjets. The advantages result from the fact that a high volumetric loading can be obtained, which leads to compact designs. Therefore, the DR is attractive for smaller applications where missile weight and small volume are required, like medium-range air-to-air missiles and ground-to-air missiles [3, 4, 5]. The typical disadvantages of liquid fuel ramjets do not appear for this type of propulsion system. The mass flow of a ducted rocket gas generator cannot be varied over the extensive ranges that are possible for an LFRJ. Fuel flow regulation valves were successfully applied in tests, however, covering a wide range of missions [6]. It is clear that these devices increase the complexity of the motor and also induce their own difficulties like exposure of the valve to the hot gases (material choice), deposits of propellant (efficiency), and combustion instability (dynamic effects). Mass flow regulation also requires special tailoring of the gas generator propellant (pressure sensitivity and stable response to changes in valve throat area).

A special category of fuel flow regulation is employed by unchoked ducted rocket gas generators. For these types of gas generators, the propellant mass flow is dependent on the ram air pressure, in contrast to a choked gas generator that generates its own internal pressure. For the latter, the combustion process is autonomous. The advantage of unchoked gas generators is the absence of a special fuel mass flow regulation device, whereas the mass flow adapts to the missile's velocity and height. This type of gas generator requires special tailoring of the gas generator propellant (pressure sensitivity and suitable response to pressure changes).

All modern ramjets with a boost phase will have solid propellant boosters that are integrated in the ramjet combustion chamber to form an Integral Rocket Ramjet (IRR). The typical feature of an IRR system is the booster nozzle, which is either jettisoned to form a larger ramjet nozzle at the end of the boost phase[1], or formed by the propellant shape ('nozzle-less' booster). This is shown in Figure A.4. The latter concept is applied in the Matra/ONERA 'Rustique' test motor missile[2]. The advantage is the absence of potentially dangerous flying metal objects (collision

1 A larger ramjet nozzle is needed because of the lower internal pressure compared to the boost phase.

2 It is worthwhile mentioning that the Rustique also applies an unchoked gas generator. Both the absence of a fuel flow regulating device and a nozzle lead to a reduction in weight.

with launch aircraft or damaging/endangering ground equipment/personnel). The performance is generally lower (15% to 25% for I_{sp}), but this may be compensated by a well-chosen design [3]. The application of a nozzleless booster requires special tailoring of the booster propellant due to the distinct ballistic conditions (higher burn rate required, erosive burning, low residence time, increasing inner bore and burning surface) and the larger mechanical loads (large pressure differential between head-end and aft-end). This will lead to higher design costs, but the result is a simpler (lower production costs) and more reliable (and safer) system. The system weight will be slightly higher compared to a booster with a nozzle [3].

In Chapter 2, ramjet-powered missiles will be compared to conventional rocket systems, following the life cycle of acquisition (costs), operational use and disposal (incineration). The pros and cons of ramjet propulsion are outlined. The international developments are addressed in Chapter 3.

2 Advantages and disadvantages of ramjets

2.1 Performance

The principal advantages of conventional rocket motor propulsion are simplicity and compact design. Solid propellant rockets are the most efficient propulsive means for tactical missiles as long as relatively short ranges are required. Nowadays, everywhere in the world tactical missiles must be capable of higher performance in terms of range, speed and manoeuvrability with a low risk of detection and interception (e.g. low altitude flight). With a conventional rocket motor, an increase in performance is not achievable without a considerable increase in weight and size (more propellant). Careful planning of the ballistic trajectory may improve performance but only at the expense of mission flexibility. At the price of relatively little extra cost and system complexity, these disadvantages are overcome with ramjet propulsion.

The advantage of air-breathing propulsion arises from the higher specific impulse I_{sp} (the thrust impulse per unit propellant weight) compared to rockets, which results from the fact that the oxidizer is not to be carried along during the flight but is taken from the atmosphere. This is illustrated for several air-breathing motor concepts in Figure A.5. For low Mach numbers, the turbojet and turboramjet engine are the most efficient. Turbojets and turboramjets are complex and heavy systems and are generally only applied in aircraft or very long-range tactical precision missiles. In the supersonic regime from Mach 3 to Mach 6, the ramjet is the most efficient propulsion system. Maximum values for the specific impulse are typically between 6 to 8 times higher for ramjets than for conventional rocket motors. At flight speeds above Mach 6, the total pressure losses in the inlets are high, and the static temperatures of the airflow, entering the combustion chamber, are so high that it is difficult to add energy by combustion. These effects lead to a drop of I_{sp} for ramjets. In addition, the extremely high static pressures require heavy structures. Above flight speeds of Mach 6, the Supersonic Combustion Ramjet or SCRamjet is the most efficient propulsive means. For this type of ramjet, combustion takes place at supersonic gas speeds. This requires less deceleration (compression) of air in the inlets, leading to a more efficient inlet efficiency (less pressure drop) and lower static temperatures and static pressures. The practical application for missile systems has been limited until now to ramjets, but in France (and also in the US, Israel and the CIS), scramjet research for missile application is being carried out as a further development in ramjet propulsion.

The high specific impulse of ramjet propulsion allows the design of missiles that are capable of longer ranges compared to rocket motors with the same amount of fuel, and a powered flight all the way to the target. A longer powered flight is

desirable if high manoeuvrability is required (e.g. fast moving targets, evasive manoeuvres for highly defended targets). Lighter and smaller missiles may be designed if no increase in range is pursued but only higher velocity, higher manoeuvrability and better aircraft integration.

An example of a ramjet-powered missile vs. a conventional solid rocket missile is given in [7]. Consider a missile with an operational range of 100 km and a payload of 200 kg with a cruise speed of Mach 2 at low altitude (Figure A.6). A solid propellant rocket solution would require a missile with a length of 9 to 10 m and would weigh about 5 tons. An LFRJ-powered missile with integrated booster motor would have a length of about 6 m and weigh only 1 ton. An even more compact design would be obtained for a ducted rocket design.

The choice of a ramjet depends on the mission requirements. It is clear that if system weight is a critical factor (e.g. for air-to-air applications), the extra system weight introduced by the DR fuel control mechanism, inlets and other systems must be compensated by the reduction in missile weight compared to a conventional solid rocket motor. This will be more critical for smaller systems. Insight into exact weights of typical ramjet sub-systems is required to make a justified trade-off between a ramjet or a rocket option. This dilemma is illustrated by the protests that arose to a Variable Flow Ducted Rocket (VFDR)-system by the F-22 program office in the Pre-Planned Production Improvement (P^3I) of Hughes' AMRAAM [8]. The F-22 program office believes that a VFDR missile is likely to weigh more than the 156 kg of today's AMRAAM and was resisting any increase in missile weight. For AMRAAM, no extended range is required, but a greater manoeuvrability at the edge of the range envelope. To solve this problem, a dual boost motor with an unpowered intermediate coast phase has been suggested. The price that is payed for this solution is probably a lower mission flexibility. Other programmes like the European counterpart to AMRAAM, the A3M and S22XR options for FMRAAM consider a ducted rocket option to achieve a long range with large growth potential (range roughly twice as high as for the current AMRAAM) and high manoeuvrability.

The employment of a ramjet urges the development of other missile sub-systems, which may be regarded as a drawback (high development costs) but which is inevitable for advancements in missile performance. An example is the maturation of smaller diameter radar seekers that are capable of functioning in both bank-to-turn and skid-to-turn steering mode. For the A3M control, DASA thinks of starting in bank-to-turn mode and changing to skid-to-turn mode during the last few seconds of its approach to the target when the missile switches to its onboard radar and target acquisition [9]. For long-range missiles the general problem is target recognition and target allocation. Nowadays medium-range missiles like the AMRAAM have BVR capability and it is likely that IFF (Identification Friend or Foe) developments will further promote the use of longer-range (ramjet-powered) missiles.

Another difficulty results from the aerodynamic heating of the missile body that is a consequence of the high speeds, attained with ramjet propulsion. This requires improved cooling concepts for (mainly IR) seekers. Also, good insulation of the gas generator propellant (DR application) is required to prevent coning of the grain that may result from a higher burn rate towards the outside of the gas generator grain.

2.2 Development costs

Development of a ramjet-powered missile typically took 8 to 10 years for the present operational systems. With the vast experience that exists nowadays in France, Germany and the US, procurement costs for newly developed ramjet-powered missiles will possibly be of the same order as for conventional rocket motor systems. Costs will probably be mainly dictated by new developments in tracking (guidance) systems. Ramjet system development will be dictated by special cost drivers. This is illustrated next.

From a technical point of view, liquid fuel ramjets are the most mature type of ramjet. For this type of ramjet, typical problems arise when using slurry fuels if a high volumetric loading is desired. This would probably lead to the choice of a ducted rocket (solid propellant gas generator). The development of a good gas generator propellant is more difficult, however, than the development of a standard composite propellant because of the special difficulties that arise from (partly) conflicting requirements:

- high performance (high volumetric loading, high combustion efficiency, low amount of deposits);
- low signature.

In order to attain a high volumetric heating value of the gas generator propellant and a maximum specific impulse, the gas generator propellant is oxygen deficient and contains a large amount of metal particles. In theory, the highest theoretical performance (in terms of I_{sp}) is obtained for the highest solid loading (highest energetic value per unit of volume). In modern systems, the propellant is frequently metallized with boron. In practice, the amount of metal particles added to the fuel is limited due to the producibility of the grain (viscosity during mixing and casting) and the expulsion efficiencies that are lower for higher solid loadings, especially for non-choked (self-regulating) gas generators [10]. In addition, metal particles are more difficult to combust, which leads to a lower combustion efficiency and, consequently, to a lower nozzle efficiency because the remaining particles in the gas flow cannot be expanded. Hot radiating metal particles also increase IR signature and visibility due to the formation of primary smoke. In order to obtain a high volumetric loading (compact design), end-burning grains must be

applied which requires special (expensive) tailoring of the propellant's burn properties (burn rate catalysts).

As for common solid propellant grains, ingredients that require sophisticated or time-consuming processing procedures will generally be avoided. Ref. [6] states that all processability problems are similar to conventional solid composite propellants. Usually, the required mechanical properties of the solid propellant gas generator are not so severe compared to conventional solid propellants (depending on the grain configuration). The grain of a solid fuel gas generator is preferably end-burning (cigarette burning) so there is only minor stress loading due to the propellant's own weight, and ignition pressurization. Thermo-mechanical straining (as a result of cool-down during storage or operation at high altitudes) may be high, however, for these configurations.

Besides the fact that a solid propellant gas generator may be more difficult to design compared to a conventional composite propellant (higher design costs), higher recurrent costs may arise from:

- special fuel ingredients (boron, burn rate catalysts);
- application of sophisticated designs and materials (ram combustor liner, nozzle);
- ramjet subsystems (inlet, diffuser, fuel flow regulation valve, etc.).

Some high energy fuel components, like metals or metal compounds, are relatively expensive and may raise the costs of propellant manufacturing if they are applied in large quantities [6]. Some characteristics of the propellant, like a very high combustion temperature or a very high particle loading, may raise the system costs due to the need for a sophisticated design or exotic materials [6]. Aspects of liner formulation concerning adhesion or migration problems are similar for DR and conventional composite propellants. However, different from customary solid rockets, aerodynamic heating occurring during long flights at high Mach numbers may warm up the propellant and may cause conical burning. The ram-combustor liner is exposed to hot gases for a long time. In [6], problems were experienced as a result of combustion instabilities during the ramjet phase that damaged the liner.

As for the liner, the nozzle too is exposed to high temperatures for a long time. High temperature melting metals cannot be used because of the unacceptable weight penalty, while ceramic parts are extremely expensive and are difficult to manufacture. According to [6], the solution may be steel nozzles with thermally resistant coatings (spinel, zirconium-oxide), graphite nozzles or special carbon-based nozzles.

Finally, it is obvious that the special ramjet parts like inlets, diffuser and fuel flow regulation valve give rise to increased development, design and manufacturing costs compared to conventional rocket motors. It is believed that most of these

parts nowadays have reached a state-of-the-art status and complex (heavy and costly) systems are generally avoided.

Because ramjet systems are more complex than rocket systems, maintenance costs are probably somewhat higher (see Section 2.6).

2.3 Safety

New developments of conventional solid propellant rocket motors tend towards better IM characteristics (Insensitive Munitions). Modern rocket motors must be designed such that they are less sensitive to shock, impact, friction, fire and sympathetic detonation than their predecessors (US MIL-STD 2105 and French MURAT IM requirement documents). Two safety aspects are considered here:

1 Operational safety;
2 IM characteristics.

Depending on the application that is considered, the operational safety of a ramjet-powered missile is not necessarily different from that of a conventional solid rocket motor system. For air-launched applications, it is not desirable that the booster nozzle is jettisoned. In these cases, a nozzleless booster may be considered at the expense of decreased performance (see Section 2.1).

Solid fuel ramjets which have an inert binder as a fuel have the most favourable safety (and IM) characteristics. The inert binder will not react differently from any other flammable elastomeric material when exposed to thermal and mechanical aggression (fire, bullet impact). No vigorous reactions are expected.

Liquid fuel ramjets are considered to be less safe due to the inherent problems associated with leaking and vapours that may be formed consequently. It should be mentioned, however, that the modern synthetic liquid fuels used today have better safety properties than earlier used distillate fuels[3] because they are more easy to extinguish because they mix (emulsified) with water, whereas distillate fuels float on water and continue burning [2]. In addition, they are quite easy and safe to handle compared to distillate fuels and are relatively non-toxic.

Comparing a ducted rocket system (solid propellant gas generator) with a liquid fuel ramjet, the former is intrinsically safer with respect to fire hazards due to the absence of liquids that may leak (mainly naval application consideration). Compared to conventional solid propellant rockets, the liquid fuel ramjet is considered to be more vulnerable to an enemy attack or heat loads from the environment

3 Synthetic fuels like RJ-4, JP-10, RJ-5, RJ-6 and RJ-7 are pure compounds or mixtures of pure compounds with relatively high densities and high heating values. Classic petroleum distillates contain hundreds of compounds with varying structure and have low densities.

because the stored fuel is likely to burn and leak away, which may cause serious collateral damage.

Note: For all missile systems that employ a booster, the overall IM characteristics will be probably governed by the booster grain.

The available (open) literature provides some information on the sensitivity characteristics of ducted rocket propellants. In [10] and [11], figures are given on cook-off, friction and impact sensitivity of several families of ducted rocket propellants that have been developed in France by SNPE over the last decennia. The propellants find their application in the Matra/Onera 'Rustique' exploratory missile (self-adaptable non-choked gas generator) and choked gas generator concepts. A summary of the data given by [12] (ducted rocket data) and by [10] (conventional composite propellant data) is shown in Table 2.1. It is not exactly known how the cook-off test, referred to in [10], was performed. The results show favourable sensitivity characteristics for the ducted rocket propellants with a somewhat low value for the cook-off test (though the exact test procedure is not known, this was also remarked on by the authors of [10]). Low cook-off temperatures are generally considered as favourable, due to the vigorous effects of AP propellants at high temperatures.

Table 2.2 shows the result of further developments by SNPE on ducted rocket propellants [11]. For the given data, the developed families of propellant show favourable IM characteristics with respect to bullet impact and cook-off. The data may be compared to the data given for composite rocket propellants in Table 2.1. The effect of cook-off is mild and exhibits combustion in all tests. The author of [11] expects a similar behaviour even in steel-cased motors. The behaviour of a DR motor in IM tests depends mainly on the high burning rate propellant used for the booster. The DR propellants discussed in [11] are considered to be very safe because of the low content of oxidizer, the high level of polybutadiene binder and the choice of AP. They generally cannot detonate due to the absence of explosives and the low content of AP.

It is concluded in [11] that it is well possible to design ducted rockets that are apt to fulfil the US MIL-STD 2105 and the more severe MURAT*** IM requirements. This is much more difficult for modern (high energy) solid propellants.

Table 2.1: IM characteristics, comparison rocket/DR propellants.

Test	Conventional composite propellants (PB/AP/al, ref. [12]) Classic	High burn rate	Ducted rocket propellants (PB/AP, Ref. [10]) No metals	35% Mg	35% Boron
Friction CSF[1] (N)	80 - 150	50 - 90	No effect	210	221 - 345
Shock, 30 kg[2] (m)	1.75 - 3	0.50 - 1.75	2.5	2.75	2.5 - 2.75
Det.[3] (No. cards)	< 1	< 1	< 1	-	-
Cook-off[4] (°C)	175	155	-	-	116 - 121
Stat. electr.[5]	Sensitive at high amounts of Al		-	Sensitive	-

Table 2.2: IM characteristics typical DR propellants.

	Ducted rocket propellants (PB/AP, Ref. [11]) No metals	29% C	35% Boron
Bullet impact test[6]	No reaction	No data	No data
SNPE test 41 (cook-off)[4]			
- Reaction	Combustion	Combustion	Combustion
- Critical temp. (°C)	116	176	143

Description of tests

1 'Julius Peters' friction sensitivity test according to SNPE ([12], test no.16). Propellant sample is fixed on a porcelain table that moves at a certain speed. During its movement, the propellant sample is loaded transversally by a fixed porcelain rod with a maximum force of 353 N. A large value for the transversal load indicates that the propellant is not sensitive to friction.

2 'Julius Peters' shock sensitivity test according to SNPE ([12], test no.17). The propellant sample is put on a steel table and loaded by a 30 kg steel fallhammer that is dropped from a maximum height of 4 m. A large height indicates that the propellant is not sensitive to shocks.

3 French detonation sensitivity (sympathetic detonation) test, described in [12]. A standard detonator is put on a number of cellulose acetate cards that are placed on a propellant sample. The cards act as a barrier for the detonation energy. A low number of cards indicate that the propellant is not likely to propagate a detonation.

4 Cook-off is the behaviour of the propellant upon a heat stimulus, e.g. due to a fire source. Several cook-off tests exist. The SNPE-developed constant temperature test (test no.41) is meant here. The reaction may vary from combustion (mildest) via deflagration to explosion (severest).

5 Tests performed to check sensitivity to static electricity. Propellant sample is loaded with an electrical spark (test described in [12]).

6 Bullet impact test according to SNPE ([12], test no. 32). Propellant sample is confined by open steel box that is punctured by an ordinary 7.5 mm calibre bullet.

2.4 Handling and transport

Generally, ramjets are smaller systems than rocket motors with comparable performances. Therefore they are less heavy and easier to handle. Vulnerable parts present on ramjet-powered missiles like the intakes, are considered to be similarly

vulnerable as the fins or aerial strips on rocket motor systems, for example. Therefore it is believed that handling is more easy or similar for SFRJs and DR-based missiles compared to a solid rocket motor system. It is not known if LFRJs require special provisions during handling and transport. Special provisions for storage (see Section 2.5) may possibly be required.

2.5 Storage

Ref. [6]: Storage and maintenance requirements and long duration storage characteristics of ducted rocket engines are similar to the solid propellant rockets being presently operational. Ducted rockets induce no additional fire hazard for storage and handling by leaking fuel. This is especially important for naval weapon systems, see also Section 2.3.

Special storage provisions may be required (venting, warning system?) for liquid fuel ramjets due to the problems involved by possible leaking of the liquid fuel. This may also require specific training of fire- brigades. Special long-term storage problems arise for slurry fuels because the suspended metal particles tend to settle out and solidify with time [13]. In addition, special heating provisions may be required for liquid fuels when the system is stored and operated at low temperature environments (cold climate or high altitudes) due to the high viscosities of some fuel types at these conditions. A problem which is typical for high viscosity liquid fuels at low temperature is the forming of 'hangup', a fuel film that sticks to the tank walls and may be significant. High viscosity and 'hangup' affect pumping, ignition, combustion and heat transfer [2].

2.6 Maintenance and lifetime

For ducted rocket systems, the maintenance is probably similar to that for conventional rocket systems. Possibly, inspection of fuel control valves is required (Ducted Rocket with fuel flow regulation). A minor increase in maintenance costs is expected, however, due to the larger quantity of limited lifetime components like explosive bolts (e.g. if an ejectable nozzle is employed). This requires more functional tests and replacements. For liquid fuel ramjets, perhaps more servicing might be needed due to the more complex (and more vulnerable) fuel feed and control system (see also storage). Depending on the type of pressure feed system that is applied, the checks on the availability of the feed system are simple or elaborate. Inspection of fuel pumps is much more time-consuming and critical than checking the pressure of an accumulator.

With respect to service lifetime, a distinction is made between liquid fuel ramjets and ramjets using either an inert solid fuel (SFRJs) or a composite gas generator propellant (DRs). For liquid fuels, nothing is known about service lifetime, other

than the typical problems associated with solidification in the case of slurry fuels (see Section 2.5). In general, modern synthetic hydrocarbon liquids like JP-10, which are used in systems like the Talos/Vandal, the Harpoon and the Tomahawk, show good long-term storage properties [2].

Solid fuels and solid composite propellants may be classified by the amount of solid fillers that is included in the elastomeric binder (like HTPB or CTPB). Conventional solid composite propellants are highly loaded. Typically up to about 80% to 90% of the propellant constituents consist of solid particles like AP, metals and additives. For these kinds of highly loaded elastomeric materials, a compromise must be sought between mechanical properties and performance. Typical ageing mechanisms for these types are:

- degradation of the binder and/or oxidizer. Examples are oxidation of the binder, hydrolysis (moisture effect), degradation of the binder due to migration of plasticizer;
- interaction between binder and particles. Examples are oxidation of the binder by the oxidizer (chemical interaction), dewetting (mechanical interaction, contact loss between binder and particles).

These ageing mechanisms will result in changed (degraded) mechanical properties. When loaded mechanically as a result of environmental conditions (e.g. thermo-mechanical straining due to cold environment for case-bonded designs, vibration, shock or acceleration during flight), these degraded mechanical properties may cause loss of structural integrity of the propellant with unreliable functioning or even mission failure as a consequence.

Solid fuels and gas generator propellants may be more easily optimized with respect to mechanical properties. The ageing mechanisms as a result of chemical and mechanical interaction between solids and binder are absent or less problematic, as long as the solid loading is low. For highly loaded fuels and gas generator propellants (e.g. metals to increase the volumetric specific impulse), identical problems may occur as for highly loaded solid rocket propellants, however. Also, degradation of the binder system, e.g. due to migration of the plasticizer, may still cause mechanical degradation of the fuel. In addition, it should be realized that, compared to conventional solid propellants, the ageing properties are generally better for solid fuels and gas generator propellants, but the mechanical properties (and therefore also the mechanical response to environmental loads) are different too. It is clear that it is important to properly tailor the fuel with regard to ageing and mechanical properties (choice of binder type, curing agent, plasticizer, additives etc.). In view of the foregoing, DR gas generator propellants may be ranged between pure fuel (as used for SFRJs) and conventional solid propellants with respect to lifetime.

Summarizing: solid fuels and gas generator propellants for ducted rockets have a large potential for long shelf-lives. It should be added, however, that missile manu-

facturers have vast experience on the ageing behaviour of solid rocket propellants, but less on solid fuels and gas generator propellants. An SFRJ or DR design should account for the inherent mechanical properties of these materials.

2.7 Environmental issues

Apart from the fact that ramjet fuels are oxygen deficient, non-smoke requirements also result in the absence of large amounts of HCl [10, 11]. With respect to this point, similar design considerations hold for ducted rockets and conventional solid rocket motors for the choice of propellant ingredients [6, 10, 11].

Disposal of liquid fuels is probably more easy because the fuel may be pumped out and may be recycled or incinerated. For solid propellant gas generators, similar problems occur as for conventional rocket motors. Due to the fact that the propellant is less sensitive (see Section 2.5), there is less risk during mechanical elaboration of the gas generator (in case this is done in the demilitarization process).

2.8 Summary table

The several ramjet types considered in this report are compared with the conventional solid propellant rocket motor in summary Table 2.3. It is emphasized that such a comparison is a rather artificial one because the advantages and shortcomings of a certain propulsion system depend on the intended mission(s) and operational requirements. We have tried, however, to draw a general outline based on the particular features of the several ramjet systems given in this chapter.

Table 2.3: Ramjet systems compared with conventional solid propellant rocket.

	SP ROCKET	SFRJ	LFRJ	DR
Performance (I_{sp})	-	++	++	+
Mission flexibility	o	-	++	+
System complexity	++	+	-	o
System maturity	++	o	+	o
Safety	o	++	-	+
Handling & Transport	+	+	o	+
Storage	+	++	-	+
Maintenance	+	++	-	+
Lifetime	+	++	++	+
Environmental issues	-	++	++	o

- Unfavourable
o Neutral
\+ Good
++ Very good

3 International developments

Presently, the major part of the European research and development activities on ramjets are carried out in France (ONERA, Aérospatiale, Matra, SNPE), the UK, Sweden and Germany (DASA). Outside Europe, the United States and the former USSR (CIS) have gained much experience on missile ramjet research. Japan performs development programmes but mainly on propulsion for (space) vehicles in the hypersonic Mach regime, and it is known that also China, India and South Africa carry out missile ramjet development activities. This chapter mainly focuses on western programmes, undertaken in Europe and the United States. Because of the potential threat by former USSR systems (widely exported to other countries), attention will also be given to Russian systems and (known) programmes.

For each of the following missile applications, the current developments will be reviewed.

- Air-launched stand-off missiles Section 3.1.
- Air-to-air missiles Section 3.2.
- Air defence missiles Section 3.3.
- Anti-radar missiles Section 3.4.
- Anti-ship missiles Section 3.5.

Finally, the development programmes on hypersonic propulsion (M > 5-6) that are not specifically linked to one of these applications will be discussed in Section 3.6.

The technical information that has been gathered during the present study for past and currently operational missile systems and development programmes is summarized in Annex A.

3.1 Air-launched stand-off missiles

There has been a considerable push for this class of missile during the past years. Most countries are more and more reluctant to risk the loss of aircrews during peace-keeping operations such as the air campaigns over Bosnia. Large losses were suffered by British Tornado fighter aircraft during fly-over tactics with JP.233 munitions dispensers [14]. For this reason, there is a tendency towards increased use of long-range, autonomous unmanned systems for rapid precision strike missions.

A further drive was given by new modern guidance concepts such as Global Positioning System (GPS) satellite navigation. In fact, GPS is the most important technological innovation in air-to-surface munitions due to its high tracking accuracy, almost regardless of range. It is not known whether GPS will demonstrate to be capable of coping with electronic jamming. GPS is less likely to be used as

terminal guidance in tactical air-to-surface weapons because these weapons are usually used against targets where precision of electro-optical guidance is necessary. The appearance of GPS guidance upgrades will make existing missiles like the US Tomahawk more versatile and has stimulated similar efforts elsewhere (see below).

Stand-off missiles may be propelled by either a ramjet or a turbojet. Because ramjets fly at supersonic speeds, they are very suitable for the interception of moving targets or highly defended targets that need high speeds and high manoeuvrability. Because of their high speeds, they increase the effect of a penetrating warhead (e.g. destruction of command bunkers). Turbojets are more vulnerable to enemy attacks due to their lower speeds (high subsonic) and will probably always have stealth requirements. They are suitable against infrastructure targets. Of both systems, developments are under way in the UK (CASOM) and France (APACHE, APTGD, ASMP). In Table 3.1, the currently ongoing developments are summarized.

In the UK, the RAF decided to finally initiate the CASOM programme (Conventionally Armed StandOff Missile), (probably) a turbojet powered missile. In France, several types of stand-off missile are currently being developed, partly based on the currently operational and ramjet-powered ASMP (Air-Sol Moyenne Portée). The French MoD selected the turbojet-powered Matra APACHE (Arme Propulsée A CHarge Ejectables) as the basis for the development of two new long-range air-launched precision strike weapons for the French Air Force [15]. The original APACHE-A is a submunition delivery missile (runway interdiction) and is currently under development by Matra/Aerospatiale. It will undergo flight tests for deployment with the French and German Air Forces in 1997. The first derivative to be developed will be an Anti-Infrastructure APACHE-C with real-time navigation updates that use the US Global Positioning System. It will be used for 'coalition warfare' like NATO or Western European Union peace-keeping and peace-enforcement operations. The second version of APACHE is called APTGD (Armement de Precision Tire a Grande Distance). This French programme is of prime political and military importance to France. It provides long-ranged unmanned precision strike capability, which is currently held by the United States and Russia. Potential threats to France from the Middle East and North Africa can be deterred. France wants to be independent of the US, which could decide to withhold GPS data if the US disagree with French military objectives. It will rely on French (Matra built) Spot and Helios spacecraft data, which is loaded into the APTGD APACHE computers before launch. The development programme is strictly French and will not be offered for co-development or export to non-French partners. Matra is prime and Aérospatiale is subcontractor (currently working on APACHE-A). Another APACHE development is the Matra SCALP programme. Because the CASOM requirements are similar to those for the anti-infrastructure APACHE, APACHE has also been offered for CASOM by Matra/British Aerospace [15].

The supersonic Aérospatiale ASMP missile became operational in 1986. The missile is air launched for nuclear missions. Currently it is under development to fulfil non-nuclear missions. This version is designated ASMP-C. ASMP-C lost the French competition for APTGD but was offered for the British CASOM. As for CASOM and APACHE, naval versions are considered [16]. The ASMP-C is the candidate successor of Aérospatiale's Exocet Anti-Ship missile. The air-launched concept may be adapted to ship or submarine launched versions, since it is small enough to fit into standard torpedo tubes, although its fins must be re-designed. APACHE is too large to fit into torpedo tubes. A follow-on for the ASMP is the Air-Sol Longue Portée (ASLP), currently under development.

Table 3.1: Stand-off missile developments.

Country	Missile	Range	Weight	Propulsion	Operational status
France					
	APACHE-A	140 km		Turbojet	Flight tests 1997
	APACHE-C	400+		Turbojet	Development
	APTGD	400+		Turbojet	Early next century
	SCALP	600 km	1250 kg	Turbojet	Development
	ASMP	250 km	900 kg	LFRJ	1986, nuclear
	ASMP-C	300 km		LFRJ	Development
	ASLP	1200 km		LFRJ (?)	Development
UK					
	CASOM			Turbojet	Development
USA					
	JASSM				
	SLAM	90 km	630 kg	Turbojet	Operational
	GRAND SLAM	Further development of SLAM			
USSR					
	?				

LFRJ = Liquid Fuel RamJet

3.2 Air-to-air missiles

A USA/European missile plan to develop a new family of air-to-air missiles was suggested in the early 1980s [17]. Germany and the UK (and later also Norway) would develop a third generation short-range weapon: the ASRAAM (Advanced Short Range Air-to-Air Missile), while the US would focus on the development of the AMRAAM (Advanced Medium Range Air-to-Air Missile). The ASRAAM programme was abandoned by Germany because it was considered too costly. There was no joint USA/European plan anymore and important know-how was about to be lost. However, BAe has further developed the concept, using a US (Hughes) seeker. Germany decided to further develop the IRIS (Infra Red Imaging Seeker) to prevent overall dependence of the US for their missiles. In the US, own developments for a next generation short-range missile were continued (AIM-9X).

Also for long-range air-to-air missile developments, the US and Europe deployed their own development activities.

Short-range air-to-air missiles
The development of a new short-range air-to-air missile as a successor of the outdated AIM-9 Sidewinder was speeded up due to the appearance of the Russian R-73, AA-11 'Archer' [8]. In close combat, this missile was comparable if not superior to AIM-9L/M/R Sidewinder series. Several programmes should meet the requirements for a new generation of IR-guided short-range missiles. In the US, the AIM-9X program is being developed to replace the 20,000 AIM-9s currently in service in the US. Parallel developments in other countries are the British ASRAAM, the French MICA and the Israelian Python 4. The German MoD has decided to further develop its IRIS-T concept with Thrust Vector Control (TVC) for its FSRAAM programme (Future Short Range Air-to-Air Missile) [18]. This missile should have better performance than the AA-11 'Archer' and the US AIM-9X and should be less costly than the latter. The German MoD did not choose ASRAAM because it is considered to be less agile in Close-In-Combat (CIC). The Germans believe that high CIC capability can only be achieved with a combination of TVC and aerodynamic steering. In addition, the seeker must be acquired from American industry, which means that there is still no independence from the US. The IRIS-T IR seeker is in a progressed development phase, which means a relatively low development risk. The development costs are estimated at DM 450 million in which Germany wants to participate for more than 50%. The following countries have reacted positively to the German invitations to participate in FSRAAM: Denmark, Greece, Italy, Canada, Norway and Sweden. Discussions on an MoU with these countries were started in October 1995 and should have been signed by April 1996.

The two approaches for the AIM-9X are the USAF/Raytheon 'Box Office' programme and the Naval Weapons Centre AIM-9 modification called 'BOA'. Alternatives for the AIM-9X are the British ASRAAM, the French MICA and the Israelian Python 4.

None of the missile systems discussed above employ air-breathing propulsion.

Medium-range air-to-air missiles
The European Eurofighter-programme countries (Germany, UK, Italy and Spain) have concluded that besides an improved SRAAM, also an improved MRAAM should be developed with a better performance than the AMRAAM and the MICA [18]. The European FMRAAM requirements are formulated in the British 'Staff Requirement 1239'. The document has been harmonized with Germany. France, Italy, Sweden and probably also Spain have shown interest. Until now, France has followed its own way with its MICA with alternate active radar and IR seekers, abandoning the combination of short- and medium-range missiles [14]. A possible

French participation would lead to lower development risks because of their considerable know-how.

A DASA study for FMRAAM is the A3M (Advanced Air-to-Air Missile) using an integral rocket ramjet with a boron-loaded solid propellant gas generator (ducted rocket). A UK ITT for FMRAAM was sent in December 1995 to potential European and US companies. A US contract to an AMRAAM follow-up would mean a total dependence on the US. In Germany, European independence from the US is emphasized. Initially, Germany will buy a limited number of AMRAAMs for their F-4F Phantom fighter aircraft though.

A competitor to the German A3M is the medium/long-range (BVR) S225X(R) (S for stealth, X for experimental, R for Ramjet) [19, 8, 20]. BAe, Saab, Alenia and GEC-Marconi have teamed up to develop a missile that is aimed at a 40% improvement over the AMRAAM in overall performance at roughly the same market price to prevent a global AMRAAM monopoly. The S225X(R) is likely to be ramjet-powered. This will probably require a French ramjet motor, because nowhere else is ramjet technology considered to be developed far enough.

The development of Hughes' AMRAAM is planned in three phases, the Pre-Planned Production Improvement (P^3I) [8]. In the first phase, the AMRAAM was developed and produced. AMRAAM has been in full production since 1994 for the USAF F-16, F-15 and F-22A. The missile is designated for the Eurofighter 2000 and Sea Harrier FRS.2. The UK, Finland, Norway, Korea and Turkey have been cleared to receive the weapon. The AIM-120B (AMRAAM with electronically reprogrammable signal processor) will start in 199(?). The AIM-120C is a clipped wing AMRAAM for integration in the F-22A's belly weapon bay. In Phase 2, the weapon's ECCM capability will be improved, and its manoeuvrability in Phase 3. A better manoeuvrability is chosen rather than an extended range. For this purpose a Variable-Flow Ducted Rocket (VFDR) is being developed by Hughes. Also lower-cost approaches are being studied, including a more compact front-end design and a longer motor, a larger diameter motor or a two-pulse motor. AMRAAM office is defining demonstration programs for a review of Phase 3 in late 1996 or early 1997.

Russian counterparts are a ramjet version of the R-77, designated R-77M/RVV-AE-PD and is currently under development according to [14]. Note the nearly 80% range improvement against a weight penalty of only 20% for this missile [14]. Also an updated version of the R-33 (designated R-37) is foreseen. It is not known if this missile is ramjet-powered. Finally, a very long-range AAM, the KS-172 is probably under development. Its status is unclear [20].

In Table 3.2, the medium/long-range air-to-air missile developments are summarized together with some of the currently operational rocket-powered missiles.

Table 3.2: Medium/long-range air-to-air missile developments.

Country	Missile	Range	Weight	Propulsion	Operational status
Europe					
	Sky Flash	45+ km	193 kg	Rocket	Operational
	MICA	55 km	111 kg	Rocket	End of development
	FMRAAM			DR (?)	Development (> 2000)
	A3M	> 250 km	165 kg	DR	Development (> 2000)
	S225X(R)	> 100 km		DR	Development (> 2000)
USA					
	Sparrow	100 km	228 kg	Rocket	Operational
	Phoenix	200+ km	450 kg	Rocket	Operational
	AMRAAM	50 km appr.	157 kg	Rocket	1994
	AMRAAM/RJ	50+ km		DR	Demonstration 1996/1997
USSR					
	R-73M	40 km	110 kg	Rocket	Developmental R-73 Archer
	R-77	90 km	300 kg	Rocket	Operational
	R-77M	160 km	360 kg	Ramjet	Development
	KS-172	400 km	750 kg	Ramjet (?)	Development (?)
	R-37	300 km	499 kg	Ramjet (?)	Development (?)

DR = Ducted Rocket

3.3 Air-defence weapons

Most European army air defence units are based on systems such as the Roland and Crotale. They will need to be replace early next century. The US Army integrated its SAM programme into the European requirement under the new Medium Extended Air Defense System (MEADS) [14]. The large air defence missile market (in terms of money value) is saturated by systems like the Crotale, Roland and their Russian counterparts [14]. Also the naval surface-to-air missile production is declining. The French Aster naval SAM is closely tied to the French/Italian/British common frigate programme. The German/Dutch/Spanish Trilateral Frigate will be armed with the new Hughes Evolved Sea Sparrow (ESSM).

In [14], growing sales are mentioned for small, low-cost, man-portable missiles such as the US Hughes/Raytheon Stinger, the Matra Mistral, the Swedish Bofors RBS.70/RBS.90 and the British Shorts Starburst/Starstreak.

The more significant investments are done in favour of anti-tactical missiles [14]. The Loral Erint has been chosen for the US Army's Patriot PAC-3 requirement and the Lockheed Martin Thaad is undergoing tests. In the US, a national defence

against Theatre Ballistic Missiles (TBM) may be developed. Israel is developing the Arrow 2. Japan has shown interest in TBM defence due to the growth of North Korean missile capability. Several European countries, including France and Britain, are beginning studies to define their own requirements. Others, including Kuwait and South Korea, are discussing procurement of the mature Russian SA-12.

The only medium-range ramjet (ducted rocket) application is the SA-6, which is being replaced by the SA-11, a rocket-powered missile (see Table 3.3). The SA-6 is widely exported and still in use in countries like the former Yugoslavia, Libya, Syria and Iraq. Two long-range applications, the BAe Bloodhound 2 and the Sea-Dart, employ Liquid Fuel Ramjets.

Table 3.3: Air defence missile developments.

Country	Missile	Range	Weight	Propulsion	Operational status
Europe					
	Crotale	10 km	84 kg	Rocket	Operational
	Roland 3	8 km	67 kg	Rocket	Operational
	Sea Dart	> 80 km	440 kg	LFRJ	1973 - ?
	Bloodhound 2	213 km		LFRJ	Operational ?
	Aster				
USA					
	SM-2 (ER)	55+ km	1360 kg	Rocket	Operational
	Sea-Sparrow	18 km	205 kg	Rocket	Operational
	ESSM			Rocket	Development
	HAWK	40 km	635 kg	Rocket	Operational
	Patriot		908 kg	Rocket	Operational
	Erint (PAC-3)			Rocket	Operational
	Thaad			Rocket	Operational
USSR					
	SA-12b	100 km	1500 kg	Rocket	Operational
	SA-6	24 km	599 kg	DR	1967
	SA-11	32 km	690 kg	Rocket	Oper.,replaced SA-6

LFRJ = Liquid Fuel RamJet

DR = Ducted Rocket

3.4 Anti-radar missiles

Developments in Europe have been promoted by Matra/ONERA who have been working for years on ramjet propulsion with their MPSR (Modèle Probatoire de Statofusée Rustique) experimental missile. This self-modulated ramjet serves as a basis for application in an anti-radar weapon to replace the Matra Martel and Armat around 2000. A second application might be a beyond-visual-range air-to-air missile [21]. A test missile was flight tested with the flight profile of an air-to-air missile. The missile could be a candidate for the French ARF (Anti-Radar Future) programme, for which also Aerospatiale is a contender. Matra could coop-

erate with Aerospatiale or ONERA for propulsion development [22]. The ARF programme could also involve German and British participation. A data exchange between France, Germany and the UK has been discussed [22]. The studies focus on the new radar threats in the early 21st century and trade-offs on propulsion and missile speed versus sensor capabilities. Production in France is foreseen by Matra and Celerg (a joint venture between SNPE and Aerospatiale).

A Russian counterpart with ramjet propulsion is the Kh-31P 'Krypton', also known as 'AWACS killer'. Another missile with uncertain development status is the KS-172 probably also developed for AWACS-like targets.

In Table 3.4, the anti-radar developments are shown. The ARF data are based on early Rustique information [23].

Table 3.4: Anti-radar missile developments.

Country	Missile	Range	Weight	Propulsion	Operational status
Europe					
	Armat	90+	545 kg	Rocket	Operational, AS
	Martel	55+	531 kg	Rocket	Operational, AS
	ALARM				
	ARF/Rustique	100 km	220 kg	DR	Development
USA					
	ARM		615 kg	Rocket	Operational, AS
USSR					
	Kh-28	120 km	715 kg	Rocket (liq.)	Operational, AS
	Kh-58U	120 km	640 kg	Rocket	Operational, AS
	Kh-31P	200 km	600 kg	Ramjet	1990 (Anti-AEW)
	KS-172	400 km	750 kg	Ramjet (?)	Development (?)

AS = Air-to-Surface
DR = Ducted Rocket

3.5 Anti-ship missiles

Two types of missiles are considered here, air-launched anti-ship and ship-to-ship missiles. The latter class of missile is sometimes developed for use in an anti-aircraft role (e.g. the Hughes/Raytheon Sea-Sparrow).

Nowadays, about 60% of the systems used are based on the McDonnell Douglas RGM-84 Harpoon and the Aerospatiale Exocet [14]. They are likely to be replaced in the near future by the next-generation of ramjet-powered supersonic anti-ship missiles. Despite earlier cancellation of the common French/German ANS programme (Anti-Navire Supersonique), the key element in future Anti-Ship missile developments remains ramjet propulsion. The most near-term programme is the Anti-Navire Future (ANF) which has been renamed by Aerospatiale as ANNG (Anti-Navire Nouvelle Génération). Aerospatiale will lead the development of this

new missile, which is to replace both the French Exocet and the US Harpoon. The development is expected with a 50% DASA participation and is to begin in 1997. ANNG is the answer to the anti-ship capabilities of current modern Russian missiles like the air-launched version of the Russian Navy's 3M80 Moskit (SS-N-22 Sunburn), designated Kh-41 and the AS-16 Kickback. Aerospatiale builds on the ramjet experience of ASMP and ANS.

The Soviet Union introduced a supersonic anti-ship missile more than ten years ago: the Raduga 3M80 Moskit or SS-N-22 Sunburn, which has been upgraded at least once. Besides the Moskit, the Russians are beginning to export new anti-ship missiles that cover the operational field of the Harpoon, like the Kh-35/SS-N-25. A new development of the Kh-35, an Air-to-Surface derivative version of the Ship-to-Ship SS-N-25, was started in 1987. Because of its external Harpoon appearance, it is called 'Harpoonski' [24].

So far, nothing is known about a US ramjet follow-on for the Harpoon. Ref. [14] speculates about stealthy or a possibly 'black' supersonic development programme or further seeker innovations for the Exocet Block 2 that perhaps might be an attractive alternative. However, the US Navy has started a Concept Exploration and Definition study [25]. Part of this study is a Foreign Comparative Test (FCT) programme. The Russian MA-31 has been chosen by the USN as the Supersonic Sea-Skimming Target (SSST) requirement for the FCT work. The MA-31 is a derivation of the Kh-31 air-launched anti-ship missile (warhead and the active radar seeker modified). The SSST requirements ask for a target system to simulate the significant anti-ship cruise missile threats such as the above-mentioned 3M-80 Moskit (SS-N-22 Sunburn). The SSST will be used to test the self-defence preparedness of a ship. For this purpose, the US Navy may require up to 100 targets each year. Flight tests with the MA-31 are expected at the end of this year [25]. The launch aircraft is the F-4 Phantom. Contractor is McDonnell Douglas Aerospace. Successful demonstration could lead to multi-year procurement for the US Navy with possibilities of MA-31 exports to other NATO Navies.

Table 3.5: Anti-ship missile developments.

Country	Missile	Range	Weight	Propulsion	Operational status
Europe					
	Exocet	70 km	660 kg	Rocket	Operational, SS
	ANS	185 km	950 kg	LFRJ	Development, AS
	ANNG	150 km		LFRJ	Development, AS
	ASMP/ANS			LFRJ	Develop. uncertain
	RBS 15	150 km	598 kg	Turbojet	1984, AS
	Sea Eagle	110 km	600 kg	Turbojet	1986, AS
USA					
	Harpoon	80 km	532 kg	Turbojet	Operational, SS
	Sea-Sparrow	18 km	205 kg	Rocket	Operational, SS
	ESSM			Rocket	Development SS
USSR					
	Kh-31A	70 km	600 kg	Ramjet	1990, AS
	Kh-35	130 km	481 kg	Turbojet	Development, SS
	Yakhont	250 km	2270 kg	LFRJ	Development (?), SS
	Kh-41	250 km	4500 kg	Ramjet	1995, AS

AS = Air-to-Ship
SS = Ship-to-Ship
LFRJ = Liquid Fuel RamJet

3.6 Future developments

As pointed out in Section 2.1, the practical application for missile systems has been limited until now to ramjets with flight speeds around Mach 3. The logical next step for missile propulsion systems is the development towards hypersonic (M > 5-6) speeds. Late-detected targets or very fast (and remote) threats may be intercepted more successfully with these high-speed missiles. In Section 2.1, it was shown that at flight speeds above Mach 6, the Supersonic Combustion Ramjet or SCRamjet is the most efficient propulsive means.

High-speed (scramjet) propulsion for missiles has been extensively studied in several countries like France, the US, and the former USSR, and also Germany has started its own R&D programme [26], though the latter is primarily based on rocket propulsion. Hypersonic flight concepts and supersonic combustion have been studied and wind-tunnel tested at ONERA already since the early 1970s. The current French hypersonic programme is called PREPHA (Programme de REcherches et de technologies pour la Propulsion Hypersonique Avancée, former PRTH programme: Programme de Recherches et de Technologies en Hypersonique) on hypersonic flight and scramjet propulsion. The programme is funded by DGA (Délégation Générale pour l'Armement), CNES, ONERA, Aerospatiale, SEP, Dassault Aviation and Snecma. France possesses a well-developed test facility (Bourges-Subdray) to conduct full-scale test firings with solid fuel or liquid fuel motors, allowing the simulation of an entire mission profile. In October 1994, a

H_2-fuelled ramjet was tested at the Bourges-Subdray test facility to a speed higher than Mach 6 [19]. According to [19], the developments could lead to a new family of missiles.

- Mach 6 ramjet ground attack missile 1400 kg; max. range 2000 km; cruise altitude 32 km.
- Mach 7 scramjet air-to-air intercept missile 1130 kg; max. range 2500 km; cruise altitude 34 km.
- Mach 5.5 ramjet long-range reconnaissance UAV 3000 kg; range 3000-4000 km; cruise altitude 32-34 km.

Also a post-PREPHA phase is foreseen. PREPHA should be followed by a European collaborative effort that must include a flight test phase [27]. Germany and Russia are considered as potential partners to develop a 'scramjet powerplant validation vehicle'. This vehicle would weigh 2-5 tons and would be 7-10 metres long. It should be launched on top of a rocket for testing in the upper atmosphere. Proposals for this test vehicle were already submitted to the French authorities in 1994.

The Russian variant of the proposed French test vehicle already exists: the Hypersonic Experimental Flying Testbed, GELA [28]. This prototype for a new generation hypersonic cruise missile has been developed by the design bureau Raduga and TsAGI, Russia's Central Aerodynamic and Hydrodynamic Research Institute. The missile has already undergone test flights, according to Raduga, and should be capable of attaining flight speeds of Mach 4.5. GELA is a second-phase development, after the first phase in which ramjet propulsion research for missiles has resulted in the development of systems like the SA-6 surface-to-air missile and the 3M80 Moskit (SS-N-22 Sunburn) anti-ship missile. In a third development phase, missiles capable of flight speeds above Mach 6 are envisaged. The major problem that has been encountered with such fast missiles is guidance.

In the German hypersonic missile programme [26], flight speeds higher than Mach 6 were reached with a rocket-powered test missile. The following critical aspects for hypersonic flight were identified: guidance, aerodynamic heating, lateral thrust control (how to hit target at these speeds), warhead fragment direction.

4 Identified fields for future work

In accordance with the Royal Netherlands Air force, the following essential areas for employment of missile systems have been identified as insufficiently perceived for ramjet missile systems:

- maintenance and lifetime;
- environmental issues.

Future work on these areas will be defined in consensus with the Royal Netherlands Air force.

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6 Authentication

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Project leader/Group leader

R.F. Calzone
Author

Annex A Figures

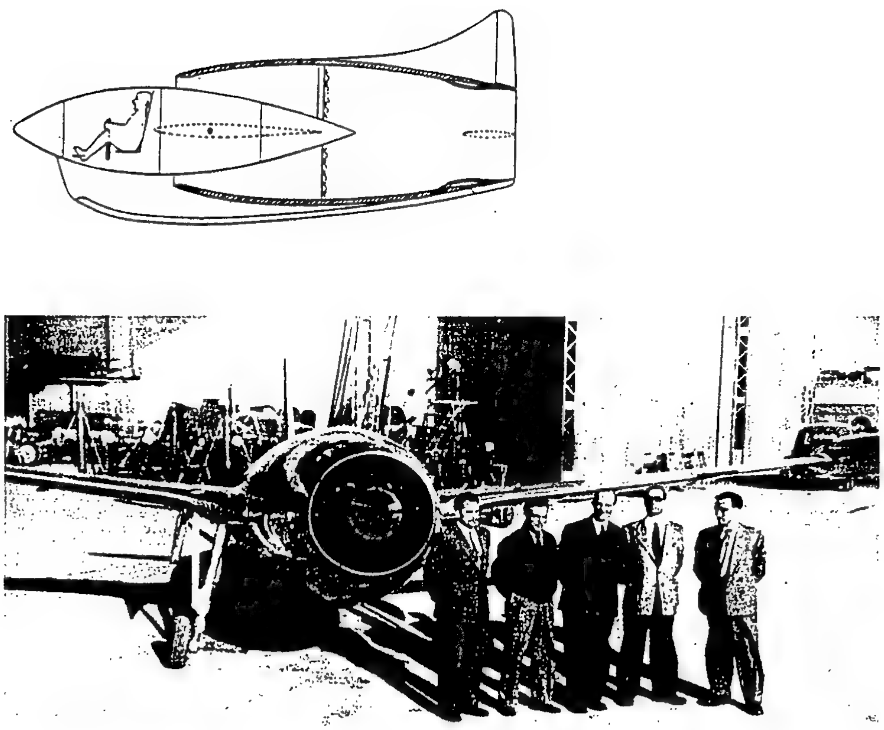


Figure A.1: Leduc 010 (1946).

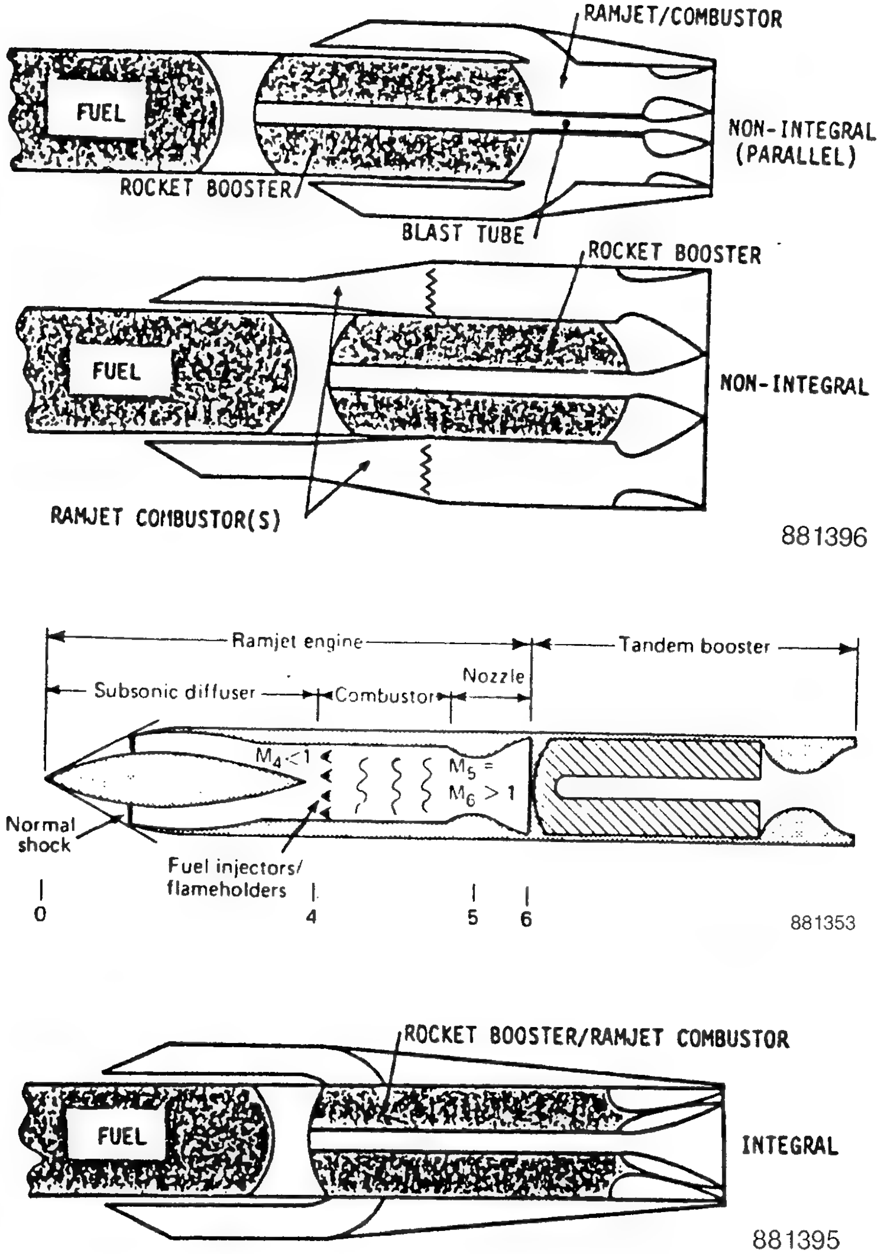
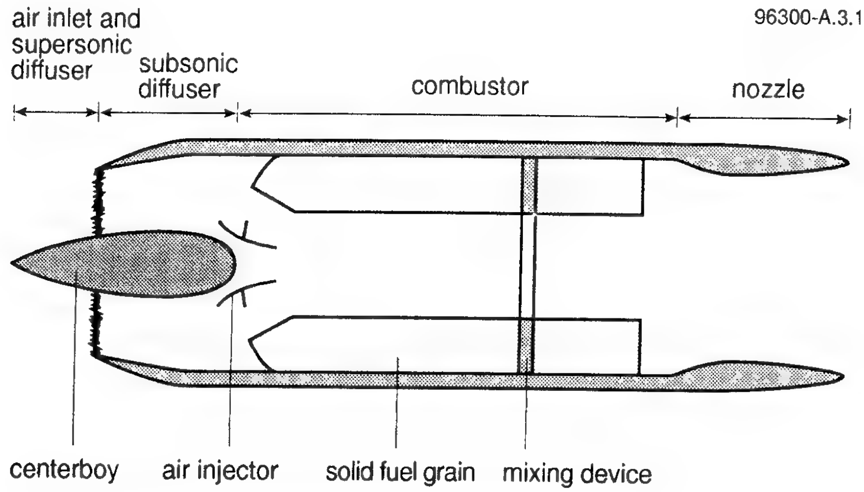
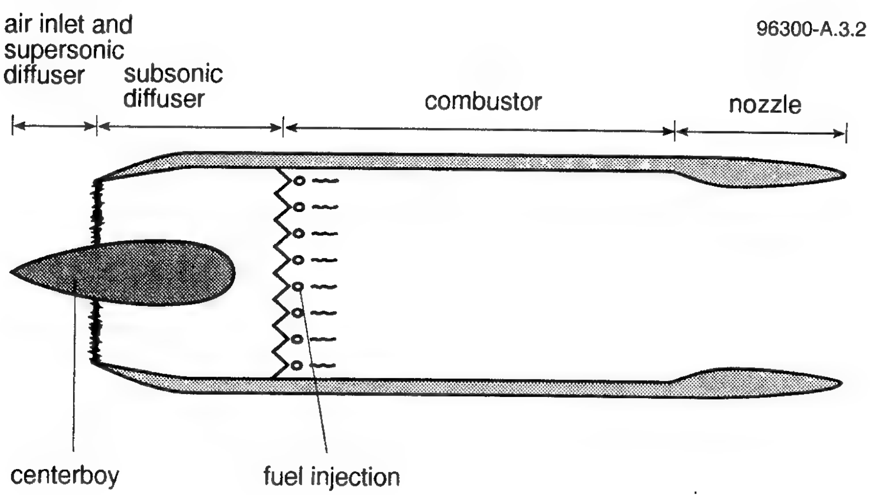


Figure A.2: *Historical development ramjet arrangement:*
Parallel (top);
Tandem (centre);
Integral (bottom).





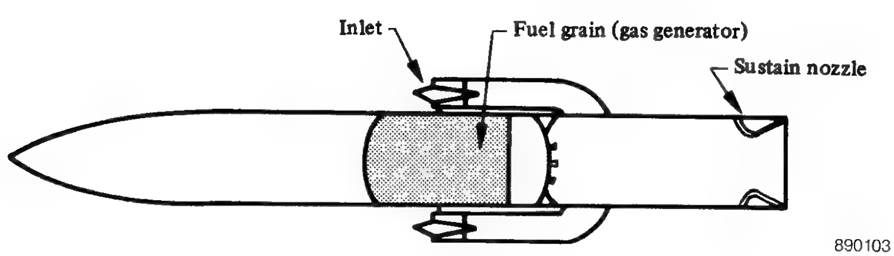


Figure A.3: *Three basic ramjet types:*
Solid Fuel Ramjet (top);
Liquid Fuel Ramjet (centre);
Ducted Rocket (bottom).

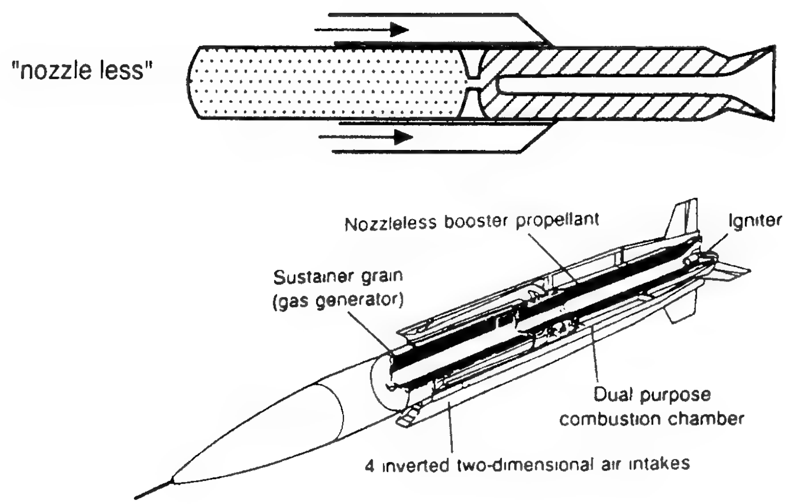


Figure A.4: *Nozzleless booster concept and example: MPSR 'Rustique'.*

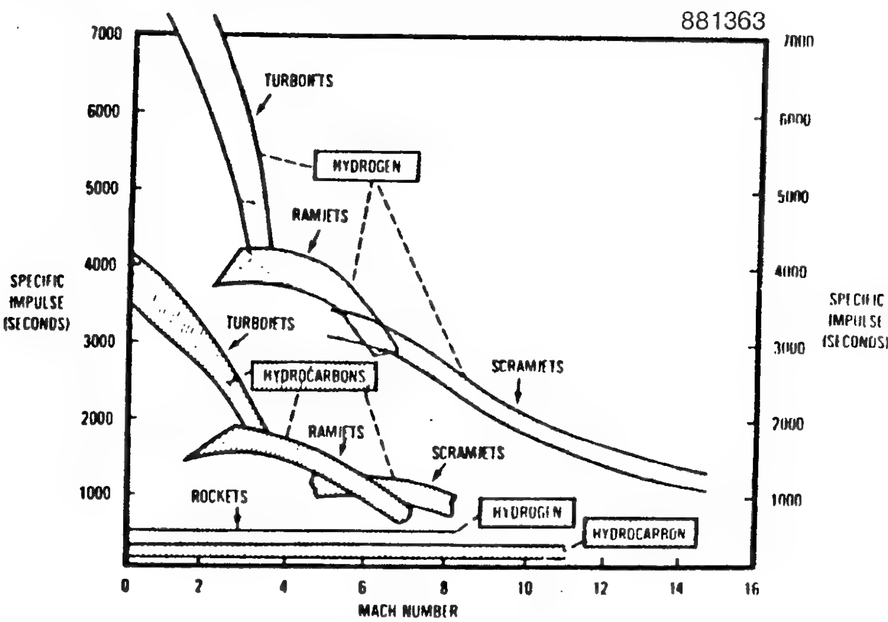


Figure A.5: *Specific impulse vs. Mach number.*

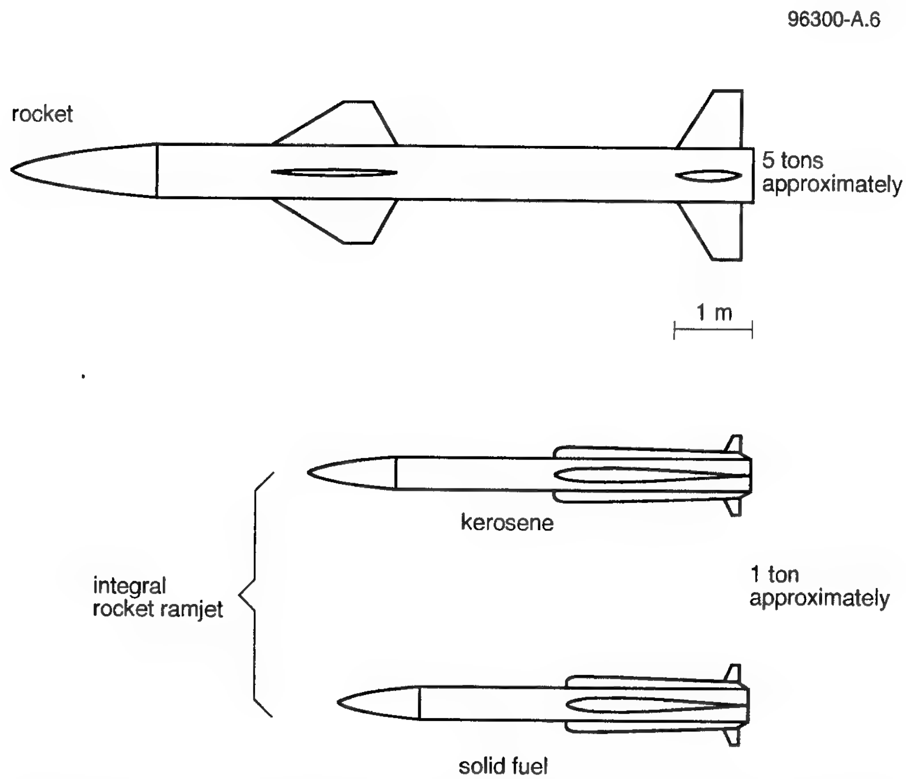


Figure A.6: Ramjet-powered (integral rocket ramjet) vs. conventionally rocket-powered missile.

Annex B Missile system information

AAM: MICA [29]

Application	Medium range air-to-air missile
Length	2.96 m
Max. body diameter	152 mm
Fin span	488 mm
Guidance	IR, inertial/active radar
Weight	111 kg
Max. range	50 km approx.
High alt. range	
Low alt. Mach	
High alt. Mach	
Development	End of development
Service	

AAM: AMRAAM [29]

Application	Hughes/Raytheon Advanced Medium Range Air-to-Air Missile
Length	3.66 m
Max. body diameter	183 mm
Fin span	640 mm
Guidance	Inertial mid-course, active terminal radar
Weight	157 kg
Low alt. range	
High alt. range	
Low alt. Mach	
High alt. Mach	
Development	
Service	

AAM/SAM: Evolved Sea Sparrow Missile (ESSM) [30]

Application	
Length	
Max. body diameter	
Fin span	
Guidance	
Weight	
Range	Aimed at 2 x range Sea-Sparrow
High alt. range	
Low alt. Mach	
High alt. Mach	
Development	Development started
Service	

SAM/SSM: Sea-sparrow (RIM-7H) [31]

Application	Short-range surface-to-air/anti-ship missile
Length	
Max. body diameter	
Fin span	
Guidance	CWSAR
Weight	205 kg
Range	1 - 18 km
Altitude	15 - 5000 m
Mach	1 - 2
High alt. Mach	
Development	
Service	

AAM: Sparrow (AIM 7F) [31]

Application	Medium/long-range air-to-air missile
Length	3.66 m
Max. body diameter	203 mm
Fin span	
Guidance	Semi-active radar homing
Weight	228 kg
Range	50 - 100 km
High alt. range	
Mach	4
High alt. Mach	
Development	
Service	

AAM: Aspide [31]

Application	Medium/long-range air-to-air missile (also SAM, [29])
Length	3.70 m
Max. body diameter	200 mm
Fin span	
Guidance	Semi-active radar
Weight	200 - 220 kg
Range	50 - 100 km
High alt. range	
Mach	2 - 4
High alt. Mach	
Development	
Service	

ASM: Exocet AM 39 [29, 31]

Application	Medium-range air-to-surface missile (anti-ship)
Length	4.70 m
Max. body diameter	350 mm
Fin span	1008 mm
Guidance	Inertial + Active radar homing
Weight	650 - 660 kg
Range	52 - 70 km
High alt. range	
Mach	0.93
High alt. Mach	
Development	
Service	

SAM: Standard missile 2 (ER) [29]

Application	Medium/long-range surface-to-air missile
Length	7.90 m
Max. body diameter	330 mm
Fin span	1560 mm
Guidance	Command/inertial, semi-active RF terminal
Weight	1360 kg
Range	50+ km
High alt. range	
Mach	
High alt. Mach	
Development	
Service	

AAM: Phoenix AIM-54A [29, 31]

Application	Long-range air-to-air missile
Length	3.96 m
Max. body diameter	380 mm
Fin span	900 mm
Guidance	Semi-active radar/active radar homing
Weight	450 kg approx.
Range	200+ km
High alt. range	
Mach	5+
High alt. Mach	
Development	
Service	

Aerospatiale Air-sol Moyenne Portee (ASMP) [23, 32, 33, 34, 20]

Application	Nuclear delivery air-to-surface missile, carried by French Mirage 2000N, Mirage IVP and Super Etendard aircraft. Ref. [20]: 300 kT nuclear warhead.
Length	5.38 m
Max. body diameter	380 mm
Fin span	956 mm.
Guidance	Inertial guidance and perhaps terrain mapping. Ref. [20]: probably terrain mapping with an onboard computer which can be programmed before launch with target location, flight profile and limited evasive manoeuvres.
Weight	900 kg; Ref. [20]: 860 kg.
Low alt. range	80 km
High alt. range	250 km
Low alt. Mach	2.2
High alt. Mach	3.0
Min launch Mach	0.60
Development	8 Years
Service	1986
Boost motor	'Alain', SNPE
Transition	Boost motor jettisoned (tandem lay-out) Ref. [32]: integral solid propellant and ramjet motor. Ref. [20]: transition at Mach 2.
Intakes	2 at either side, also serving as wings, derived from Concorde with throat bleed. Two intakes are used to achieve greater manoeuvrability during flight for evasive agility.
Fuel	Kerosene with a nominal S.G. of 0.78
Flame stabilizer	Combustion chamber head induced natural vortices
Combustor	Probable internal stakes (see ANS)
Fuel injection	Pilot and main combustion zone feed, using an HP nitrogen operated piston
Liner	Silicone elastomer loaded with refractory materials and fibres

Conventional version of Aerospatiale Air-sol Moyenne Portee (ASMP-C) (Ref. [35])

Application	Conventional warhead delivery air-to-surface missile (also ship-launched versions considered). Data given below probably less reliable than for nuclear ASMP. Uses 240 kg warhead of AS-30 Laser missile.
Length	5 m
Max. body diameter	350 mm
Fin span	
Guidance	
Weight	885 kg
Low alt. range	180 km, including a 20 km sea-skimming approach phase
High alt. range	Up to 300 km at medium altitude. Ref. [34]: 400 km or more
Low alt. Mach	
High alt. Mach	3.0
Min. launch Mach	
Development	
Service	
Boost motor	
Transition	
Intakes	
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

Aerospatiale/MBB Anti-navire Supersonique (ANS) (Refs. [23, 32, 20])

Application	Long-range, sea-skimming anti-ship missile. Ref. [32]: addition of wings could improve payload and provide a longer range. Designed for launching from aircraft, ships or ground vehicles, but small enough to fit into standard 533 mm torpedo tubes. Ref. [20]: to provide successor to Exocet and Kormoran.
Length	5.70 m (Ref. [32]: about 5.8 m)
Max. body diameter	350 mm
Fin span	Ref. [20]: 0.9 m.
Guidance	Mid-course guidance expected to be inertial, terminal active homing. Ref. [32]: active radar developed by Dassault Electronique for the terminal phase. Ref. [20]: inertial and command, active radar terminal seeker 'ADAC', developed from the AM 39 Exocet programme.
Weight	950 kg (Ref. [32]: 900 kg). Ref. [20]: 900 kg.
Low alt. range	185 km (Ref. [32]: maximum range 180 km)
High alt. range	> 185 km
Low alt. Mach	2.5 (Ref. [32]: 2.0 - 2.5)
High alt. Mach	3.0
Min. launch Mach	
Development	Started early 1980s as a replacement for the ASSM project
Service	1995 (Ref. [32]: 2000 ?). Programme terminated in 1993.
Boost motor	Ref. [32]: Integral solid propellant and ramjet motor
Transition	
Intakes	Four symmetrically placed, axi-symmetric double cone, ducted aft to enter the head dome of the integrated boost casing. Centrebody of each air intake may be translated forward for reduced drag and to serve as a protective cover during air carriage and boost phase.
Fuel	High density (S.G. = 1.1) liquid fuel, derived from ASMP, initially MBB/Bayern Chemie boron-loaded ducted rocket technology, in 1981 tested with partial success
Flame stabilizer	No details
Combustor	Internal stakes to suppress ramjet combustion instabilities
Fuel injection	No details, probably ram air pressurized bladder feeding ram air turbo-pump
Liner	

British Aerospace 'Sea Dart' (Ref. [23])

Application	Anti-aircraft and anti-missile, anti-ship
Length	4.40 m
Max. body diameter	420 mm
Fin span	910 mm
Guidance	
Weight	440 kg
Range	>80 km
Altitude	>22.9 km
Mach	2.5
Min. launch Mach	
Development	1962
Service	1973
Boost motor	Tandem boost, Royal Ordnance cast double base 'Chow' motor, thrust 15.876 kg to boost up to M = 2.0
Ramjet motor	Rolls Royce 'Odin', lighting-up during boost phase, using the boost head/ramjet exit interstage vents
Transition	Ramjet light-up during boost
Intakes	
Fuel	High density kerosene (S.G. = 0.8 +) to AVCAT grade, stored in segmental bladders in the annular space surrounding the ramjet combustor inlet duct
Flame stabilizer	
Combustor	See ramjet motor, derivative from the 'Thor' ramjet motor off 'Bloodhound 2', ram-air cooled chamber and exit nozzle
Fuel injection	Annular pilot zone and progressive source fuel jets supplying the main combustion zone. Fuel pressurized by a free-running ram air turbo pump.
Liner	

British Aerospace 'Sea Eagle' (Ref. [23])

Application	Long-range, fire-and-forget anti-ship missile (air-to-surface)
Length	4.1 m
Max. body diameter	400 mm
Fin span	1200 mm
Guidance	Inertial mid-course and radar active homing
Weight	600 kg
Range	110 km
Altitude	0 - 11 km
Low alt. Mach	0.4 - 0.9 at sea level
High alt. Mach	0.6 - 2.0 at 11 km
Min. launch Mach	
Development	1979
Service	1986
Boost motor	Two boost motors, to be externally mounted are required only for helicopter launch
Ramjet motor	Microturbo TRI 60-067 turbojet max. thrust of 350 kg at sea level, corresponding fuel consumption = 34.5 mg/Ns, design airflow = 6.2 kg/s. Engine length = 749 mm without jet pipe
Transition	
Intakes	Single underbelly scoop intake, protected with jettisonable cover during air carriage
Fuel	Kerosene
Flame stabilizer	
Combustor	
Fuel injection	Fuel injected by shaft-driven fuel pump, injected through spray burners
Liner	

Hughes Raytheon Advanced Air-Air-Missile (AAAM) (Ref. [23])

Application	Air-to-air Integral RamRocket
Length	3.66 m
Max. body diameter	230 mm
Fin span	
Guidance	Semi-active radar mid-course and terminal seeking by a combination of active radar, infrared and home-on-jam
Weight	295 kg (weight no greater than 'Sparrow')
Range	Better range/speed performance than 'Phoenix' in a launch station envelop
Altitude	
Mach	Estimated design Mach number of 2.5
Min. launch Mach	
Development	1988
Service	
Boost motor	Head-end igniter and ejectable nozzle (allow for low L/D with high I_{sp})
Ramjet motor	
Transition	Jettisoning of the domed head-end port cover
Intakes	Single two-dimensional with estimated design Mach number of 2.5 with throat bleed. Single pair of fixed wings behind inlets unfold after launch, bank-to-turn
Fuel	High density storable synthetic such as JP10, housed in a tank above the air intake.
Flame stabilizer	Annular pilot zone. Devices in the inlet port may enhance fuel/air mixing for the main zone
Combustor	
Fuel injection	Tank pressurized with ram air and fuel driven to ram air turbo-pump
Liner	Motor casing lined with insulation for operation in the ramjet mode

McDonnell Douglas 'Harpoon' (A/R/UGM-84) (Ref. [23])

Application	Sea-skimming anti-ship missile air-launched (ship and submarine launched versions have additional tandem boost of 5400 kg during 2.9 sec)
Length	3.9 m
Max. body diameter	343 mm
Fin span	914 mm
Guidance	Inertial mid-course with active phased array radar seeker terminal phase
Weight	532 kg
Range	193 km (air-launched); 80 km (ship/submarine-launched)
Altitude	12.2 km
Mach	0.85, cruise, 1.1 maximum design
Min. launch Mach	0.75 (= ramjet take-over Mach number of boosted versions)
Development	1970
Service	1978
Boost motor	
Sustainer motor	Teledyne-CAE J402-CA-400 turbojet, max. thrust = 294 kg at 41.200 RPM and air mass flow = 44.35 kg/s, SFC = 1.224 kg/hr/kg, engine weight = 46 kg
Transition	
Intakes	
Fuel	Kerosene MIL-F-81912, 49.5 kg
Flame stabilizer	
Combustor	
Fuel injection	Through nozzles in the main shaft
Liner	

Martin-Marietta Supersonic Low Altitude Target (SLAT) (Ref. [23])

Application	Simulating sea-skimming threat, refurbishment after mission
Length	5.47 m
Max. body diameter	540 mm
Fin span	
Guidance	
Weight	1.008 kg
Range	102 km
Altitude	0-1 km (9 m cruise)
Mach	2.5
Min. launch Mach	
Development	1984, derived from Advanced Strategic Air Launched Missile (ASALM), tested in 1979, 1980 at 21.3 km alt. and M > 4
Service	1991 (?)
Boost motor	Morton Thiokol integral boost motor, up to M = 2.1 in 6 seconds
Ramjet motor	
Transition	Ejection of boost nozzle and blow out of port cover, injection of fuel
Intakes	Central straight air inlet duct
Fuel	JP10
Flame stabilizer	I-Y flameholder
Combustor	
Fuel injection	
Liner	DC-93-104 loaded silicone elastomer

Matra/ONERA 'Supersonic Tactical Anti-Radar' (STAR) (Refs. [23, 20])

Application	Anti-Radar Future (ARF) missile. Ref. [20]: ARF is planned for the Rafale and in-service date of 1996 might be expected.
Length	3.8 m
Max. body diameter	350 mm
Fin span	1000 mm
Guidance	Ref. [20]: ARF, joint French/German anti-radar dual mode passive radar and IR seeker, known as SPRINT might be utilised in the ARF missile.
Weight	220 kg. Ref. [20]: ARF is believed to weigh about 180 kg.
Range	100 km. Ref. [20]: ARF range of about 100 km.
Altitude	7 km
Mach	2.5 (max.)
Min. launch Mach	
Development	1978
Service	Tested 1984. Ref. [20]: in service date of 1996 might be expected.
Boost motor	Nozzleless booster, rear-end igniter
Ramjet motor	ONERA/Matra 'Rustique' non-chocked ramrocket
Transition	As the boost charge burns out it ignites the sustainer grain and releases the inlet port covers
Intakes	Four pairs of inlets, inverted two-dimensional equi-spaced, with large throat bleed for stability
Fuel	ONERA/SNPE, regression rate chosen such that approximately constant fuel/air ratio is achieved over wide bands of Mach number and altitude
Flame stabilizer	Not specified
Combustor	Gas flow divided into four streams for efficient mixing and combustion with the air
Fuel injection	
Liner	

SAAB RBS 15 (Ref. [23])

Application	Ship-launched, sea-skimming anti-ship missile
Length	4.35 m
Max. body diameter	500 mm
Fin span	1400 mm
Guidance	
Weight	598 kg (air-launched without boosts), and 770 kg for the ship-launched versions with two 85 kg strap-on boost motors
Range	150 km (air-launched), 70+ km (ship-launched)
Altitude	
Mach	> 0.80
Min. launch Mach	
Development	1979, based on the rocket powered SAAB RB04E
Service	1984
Boost motor	
Sustainer motor	Microturbo TR-600-77 turbojet, max. (static) thrust = 350 kg at sea level, sea 'Sea Eagle' motor, weight = 53 kg
Transition	Engine starts from windmilling condition
Intakes	Single, underbelly scoop air inlet
Fuel	Kerosene, JP5
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

SA-4 'Ganef' (Refs. [36,14])

Application	Surface-to-air. 2K11 Krug (SA-4 Ganef).
Length	9.0 m; Ref. [14]: 8778 mm
Max. body diameter	800 mm; Ref. [14]: 884 mm
Fin span	2.6 m; Ref. [14]: 2560 mm
Guidance	Command guidance to vicinity of the target, where semi-active homing takes over. Ref. [14]: command guidance.
Weight	1800 kg; Ref. [14]: 2502 kg
Range	75 km; Ref. [14]: 100 km
Altitude	24.4 km
Mach	
Min. launch Mach	
Development	
Service	1964. Ref. [14]: being retired
Boost motor	Four wrap-around (solid) boost motors, ramjet delivers useful thrust during boost phase
Sustainer motor	Ref. [14]: liquid ramjet sustainer
Transition	
Intakes	Annular, downstream of ogive (uses all-movable fins for lift)
Fuel	Kerosene
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

SA-6 'Gainful' (Refs. [6, 36,14])

Application	Surface/Ship-to-air. 2K12 Kub (SA-6 Gainful). Ref. [14]: Widely exported mobile SAM. Being replaced by 9K37M Nuk-1M (SA-11 Gadfly), a DTRM with a range of 32 km.
Length	6.2 m; Ref. [14]: 6187 mm
Max. body diameter	335 mm; Ref. [14]: 329 mm
Fin span	1245 mm; Ref. [14]: 1241 mm
Guidance	Command guidance with semi-active CW homing. Ref. [14]: command guidance.
Weight	550 kg; Ref. [14]: 599 kg; Ref. [6]: 550 kg
Range	32 km at low altitude, 60 km at high altitude; Ref. [14]: 24 km. Ref. [6]: 30 to 35 km.
Altitude	
Mach	2.8 (climbing interception Mach number)
Min. launch Mach	
Development	
Service	1967
Boost motor	Integrated in ramjet combustion chamber, 3 seconds of boost phase, acceleration of 20 g
Sustainer motor	Ramrocket, thrust about 13.5 kN at separation Mach number
Transition	Ejectable boost nozzle, transition at Mach 2.5
Intakes	Four side mounted symmetrical intakes. Four movable wings and moving tabs on each of the four fixed wings reduce body incidence angle.
Fuel	Ref. [6]: gas generator with medium energy (Mg loaded) propellant.
Flame stabilizer	Spontaneous combustion of the inlet air with fuel probably does not require a flame stabilizer device.
Combustor	Ref. [6]: side dump ram-combustor
Fuel injection	Ref. [6]: fixed flow gas generator
Liner	
Max. lateral acc.	15 g
Flight time	40 seconds to 32 km

Bendix 'Talos' RIM8 (Ref. [36])

Application	Long-range SAM
Length	
Max. body diameter	
Fin span	
Guidance	
Weight	
Range	120 km
Altitude	21.3 km
Mach	2.0 at sea level and 2.5 at the tropopause and higher altitudes.
Min. launch Mach	
Development	1945
Service	1958-1985 (Target 'Vandal' still operational, simulating anti-ship missiles)
Boost motor	Tandem booster
Sustainer motor	Liquid fuelled ramjet
Transition	Ignition of ramjet after separation of the tandem booster
Intakes	25°/35° double cone air intake in the nose
Fuel	High density hydrogenated methylcylopentadiene dimer
Flame stabilizer	Can-type flame holder, based on turbojet technology. Separated pilot zone operating at optimum mixture ratio and main combustion zone, at which the fuel/air ratio can be varied from zero to a maximum near stoichiometry.
Combustor	
Fuel injection	
Liner	20% of the inlet air flow is used as a cooling heat shield
Max. lateral accel.	15 g
Max. longit. accel.	15 g

British Aerospace 'Bloodhound 2' (Refs. [36,14])

Application	Surface-to-Air missile
Length	77724 mm
Max. body diameter	546 mm
Fin span	2835 mm
Guidance	Semi-active radar
Weight	
Range	213 km
Altitude	
Mach	
Min. launch Mach	
Development	
Service	
Boost motor	Four wrap-around Solid Rocket Boosters
Sustainer motor	Two thor ramjets
Transition	
Intakes	
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

'Rustique' (Refs. [36, 23, 37])

Application	The ONERA 'MPSR Rustique' rocket-ramjet programme is one of the most ambitious from the standpoint of both French technology and US basic research cooperation. It is a dedicated French programme but with a US basis research element. Initial ONERA rocket ramjet program was halted in the mid 1980s after five flight tests. The current effort is stimulated largely by French Gulf War experience, which showed the need for a more advanced anti-radiation missile to replace the French Matra Martel. US basic research cooperation parallels the French applied research objectives for the project.
Length	
Max. body diameter	
Fin span	
Guidance	
Weight	
Range	
Altitude	
Mach	
Min. launch Mach	
Development	
Service	
Boost motor	
Sustainer motor	ONERA/Matra 'Rustique' non-choked integrated ramrocket (Ref. [23], 23). Ref. [37]: No throat between the gas generator solid propellant motor and the ramjet. The gas generator performance will be adjusted automatically to obtain proper ramjet performance throughout the missile's flight envelope. Achieved by modelling the propellant grain and creating motor sensitive to the pressure conditions in the ramjet combustion chamber (major French technology innovation).
Transition	Ref. [37]: Ramjet self-ignites using the plume from the motor.
Intakes	Four equally spaced 2-D inverted intakes (from figure in Ref. [37]).
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

KH-31 (AS-17) 'Krypton' (Refs. [38, 20, 25, 24])

Ref. [20]: at recent exhibitions, the missile has been seen fitted to Su-271B 'Flanker', Mig-29K 'Fulcrum' and Su-25T 'Frogfoot' aircraft. Also believed: Mig-27 'Flogger', SU-17 'Fitter', SU-24 'Fencer'. X-31 is export designation. Warhead 90 kg HE blast fragmentation. Aimed specifically at US MIM-104 Patriot and AN/SPY-1 Aegis phased-array radar systems. Upgraded version is reported to be in development for use as an air-to-air missile against AEW aircraft (AWACS). Other variant is used as supersonic target for ship defence training. Ref. [25]: MA-39 is USN acquired version of Kh-31 for use in Foreign Comparative Test (FCT) for Supersonic Sea-Skimming Target (SSST) requirement.

Application	Kh-31A: active seeker Anti-Ship and Kh-31P: Anti-Radiation homing type.
Length	Length of motor about 2/3 of total length. Ref. [20]: Kh-31A/P ==> 2.70 m (MOD 1) and 5.23 m (MOD 2)
Max. body diameter	Ref. [20]: Kh-31A/P ==> 360 mm
Fin span	Ref. [20]: Kh-31A/P ==> 1.15 m
Guidance	Kh-31A inertial with active radar and Kh-31P inertial with passive radar terminal seeker. Both guidance types reported to operate in ECM environments. N/K fuze.
Weight	Ref. [20]: Kh-31A/P ==> 600 kg
Range	Well in excess of 100 km. Ref. [20]: Kh-31A ==> 50 km (MOD-1) and 70 km (MOD-2) Kh-31P ==> 150 km (MOD-1) and 200 km (MOD-2)
Altitude	Kh-31A reported to have maximum range of 50 km (MOD-1) or 70 km (MOD-2) when fired from an alt. of 15 km and min. range of 5 km.
Mach	About 4.5. Ref. [20]: cruise Mach number of 3. Ref. [20]: maximum speed just under Mach 3.
Development	1980s; Ref. [20]: late 1970s as follow-on to the AS-12 'Kegler' (see Ref. [24]: Surface-to-Air missile)
Service	Currently operational. Ref. [20]: entered service in 1990
Boost motor	Solid rocket motor
Sustainer motor	Integral ramjet.
Transition	At Mach 1.8 ramjet ignites, motor (?) is jettisoned
Intakes	Four air intakes (equally spaced); conical external compression surfaces

SS-N-22 Sunburn (Refs. [14, 20])

Application	3M80 Moskit (SS-N-22 Sunburn) and 3M82 Moskit-M (improved Moskit, also SS-N-22 Sunburn). Supersonic anti-ship missile. On Nanuchka and Sovremenniy ships. See also KH-41 (air-launched version of the Moskit). Integral rocket/ramjet
Length	3M80: 9388 mm, 3M82: 9723 mm
Max. body diameter	3M80 & 3M82: 1298 mm. Ref. [20]: air-launched smaller diameter.
Fin span	3M80 & 3M82: 1890 mm
Guidance	Inertial/active radar
Weight	3M80: 3954 kg, 3M82: 4504 kg
Range	3M80: 92.6 km, 3M82: 120 km
Altitude	
Mach	
Min. launch Mach	
Development	
Service	Ref. [20]: believed that 3M80 ship-launched version entered service in 1980.
Boost motor	Solid rocket
Sustainer motor	Ramjet
Transition	
Intakes	Four long intakes.
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

KH41 (Air-launched version of the SS-N-22 Sunburn, Refs. [14, 20, 24])

Soviet Union introduced supersonic anti-ship missile, Raduga 3M80 Moskit (SS-N-22 Sunburn), more than a decade ago and it has already undergone at least one major upgrade. Besides Moskit, the Russians are beginning to export new anti-ship missiles that cover the gamut from the Harpoon look-alikes (Zvezda Kh-35/SS-N-25). Widespread proliferation of such weapons is the US Navy's worst nightmare. Russian counterparts of French/German ANNG: SS-N-22 Sunburn, air-launched Moskit and AS-16 Kickback. Warhead: 320 kg HE or nuclear. Ref. [20]: Kh-41 is designed against individual ships or convoys and could well be intended as a replacement for AS-4 'Kitchen' and AS-6 'Kingfish' air-to-surface missiles. Believed that Kh-41 will be cleared for use on some Russian naval bomber aircraft and has been seen fitted to naval Su-27K variant 'Flanker' aircraft. Ref. [20]: based on 3M80 SS-N-22 Sunburn.

Application	Air-to-Surface Missile, Anti-Ship. Air-launched version of the SS-N-22 Sunburn for Su-33 naval fighter.
Length	9723 mm
Max. body diameter	762 mm
Fin span	2097 mm
Guidance	Active radar. Ref. [20]: Inertial with dual mode active/passive radar seeker which has an ECCM capability. Impact fuse.
Weight	4504 kg
Range	250 km. Ref. [20]: low-altitude sea-skimming range of 150 km. This range is reported to increase up to 250 km when the missile follows a high altitude profile before diving to low altitude for the terminal attack phase. Ref. [24]: range between 150 km and 250 km.
Altitude	
Mach	High altitude cruise Mach number of 3, low altitude cruise Mach number of 2.1.
Min. launch Mach	
Development	Missile is thought to be in final stages of development and could replace AS-4 'Kitchen' and AS-6 'Kingfish' air-to-surface missiles.
Service	Possibly 1995
Boost motor	Solid rocket
Sustainer motor	Ramjet
Transition	
Intakes	Four long intakes.
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	

Proposed extended range R-77, designated: R-77 RVV-AE-PD (Refs. [8,14])

Application	Vympel bureau proposed design: air-to-air integral rocket ramjet missile. Current non-ramjet R-77 is AMRAAM type air-to-air missile.
Length	Overall dimensions are the same as for current R-77, except for the four intakes. Current R-77 RVV-AE (AA-12 Adder) is not a ramjet design. Ref. [14]: 3597 mm
Max. body diameter	305 mm
Fin span	823 mm
Guidance	Current R-77: active radar guidance. Vympel has proposed an upgrade to the active-radar guided AMRAAM R-77 that is now in serial production to harmonize the radar intercept envelope with the weapon performance envelope. Ref. [14]: active radar.
Weight	Ref. [14]: 360 kg
Range	At altitude: 100 - 150 km. A ramjet-powered missile would greatly increase range at low altitude and could provide range in excess of 100 km at high altitude. Ref. [14]: max range = 160 km
Altitude	
Mach	
Min. launch Mach	
Development	Developmental status in 1994, not selected for development funds. However Ref. [14] states that the R-77M (R-77 with ramjet sustainer) is currently under development.
Service	
Boost motor	
Sustainer motor	Integral rocket ramjet motor
Transition	
Intakes	Four long intakes arranged in line with the tail control surfaces.
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

KS-172, proposed by bureau Novator (Refs. [8, 14, 20])

Application	Very long-range, all-azimuth, all-aspect AAM, proposed by bureau Novator. The weight penalty is obvious, while the need for the extreme range is not. Ref. [14]: Anti-AWACS missile. Ref. [20]: probably carried by Su-27 'Flanker' and Su-35 aircraft.
Length	Ref. [14]: 6005 mm; Ref. [20]: 7.4 m
Max. body diameter	Ref. [14]: 399 mm
Fin span	Ref. [20]: 610 mm
Guidance	The KS-172 would be fed updated target information from a friendly aircraft before switching to a fully-active seeker mode for terminal engagement. Ref. [14]: active radar. Ref. [20]: inertial with updates in mid-course, followed by active radar terminal guidance. Radar proximity fuse and directional HE fragmentation warhead (probably about 50 kg).
Weight	750 kg; Ref. [14]: 749 kg; Ref. [20]: 750 kg
Range	Some 400 km. Ref. [20]: AAAM-L designed for 400 km range.
Altitude	Intercepts from 3 (?) to 30 000 m, probably with the aim of intercepting high-flying recce (?) aircraft, AEW and stand-off jammers as well as cruise missile-launching bombers.
Mach	
Min. launch Mach	
Development	Developmental status in 1994, not selected for development funds. Ref. [14] does not mention that the missile is still under development however, only that it is used as an anti-AWACS missile. Ref. [20]: status unclear, but believed to be in early stages of development.
Service	
Boost motor	Ref. [20]: solid propellant boost assembly, which is believed to be jettisoned after use.
Sustainer motor	
Transition	
Intakes	
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

R-37 (Refs. [8,14])

Application	Very long-range missile, updated version of the R-33 (AA-9 Amos). Russian air force would gain more operational flexibility by opting for a mix of the RVV-AE-PD and its new updated R-33 (AA-9) missile, the R-37 over the KS-172. Manufacturer Vympel says that the R-37 has a range of some 400 km just like the developmental KS-172.
Length	Ref. [14]: 4100 mm
Max. body diameter	Ref. [14]: 378 mm
Fin span	Ref. [14]: 1006 mm
Guidance	Ref. [14]: Active radar.
Weight	Ref. [14]: 499 kg
Range	Some 400 km. According to Ref. [14]: R-33 has a range of 120 km and the R-37 a range of 300 km.
Altitude	
Mach	
Min. launch Mach	
Development	
Service	
Boost motor	According to Ref. [14], the R-33 as well as the R-37 use a solid propellant rocket motor.
Sustainer motor	No ramjet mentioned in Ref. [14].
Transition	
Intakes	
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

Air-Sol Longue Portée (ASLP) (Refs. [32, 20])

Application	Successor to ASMP, probably not before 2005. Ref. [20]: selectable yield nuclear warhead is believed to be in design. Planned that ASLP will be carried by Rafale aircraft and was offered to UK in response to UK's TASM requirement.
Length	About 5.25 m, with rear delta wing planform blended forward into the flat undersurface body. Ref. [20]: about 5.1 m.
Max. body diameter	
Fin span	
Guidance	Ref. [20]: no information on guidance systems.
Weight	
Range	800 - 1200 km.
Altitude	
Mach	Around 3.0.
Min. launch Mach	
Development	Ref. [20]: at present time, project is simply a private venture feasibility study which might enter service around 2005 to replace existing ASMP.
Service	
Boost motor	
Sustainer motor	Ref. [20]: Integral rocket/ramjet motor assembly mounted above the rear body but with the exhaust nozzle below the vertical rudder.
Transition	
Intakes	One air inlet above the body
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

ANF (renamed ANNG: Anti-Navire Nouvelle Génération), (Refs. [122, 19])

Application	ANNG: ASMP-derived anti-ship missile, successor to Exocet and Harpoon. Originally sea-based, but later also on Rafale (2002-2004) and Eurofighter 2000 (EFA) in the early 21st century
Length	
Max. body diameter	
Fin span	
Guidance	
Weight	
Range	About 150 km (double of current western systems)
Altitude	
Mach	> Mach 2
Min. launch Mach	
Development	
Service	
Boost motor	
Sustainer motor	
Transition	
Intakes	Twin-intake ramjet design over the original four-inlet option to save costs but with little performance degradation
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

Apache and derivates, (Refs. [32, 22, 15, 35])

Application	Submunition delivery standoff missile or single warhead missile. Ref. [15]: Apache selected as basis for the development of two new long-range air-launched precision strike weapons for French Air Force. Both cruise missile versions deliver about 450 kg conventional warhead over 400 km with pinpoint accuracy. Stealth capabilities. Current Apache tests at a range of 140 km, also designed to drop small submunitions, not carry a large single warhead. The primary new Apache version is designated APTGD: 'Armement de Precision Tire a Grande Distance'
Length	About 5 m (Ref. [32]). Ref. [35]: 5.1 m.
Max. body diameter	
Fin span	
Guidance	Spot and Helios (Matra built) data loaded into APTGD Apache computers before launch ==> key element in navigation to target. Until 2 km from the target APTGD uses millimetre-wave radar and inertial system; then infrared sensor will be deployed below the nose.
Weight	Around 1250 kg for Super Apache (Ref. [32])
Range	Initial range 140 km for submunition version, later 400-500 km single large warhead (Ref. [32]: 450 kg) version. Ref. [35]: Apache-C: 600 km.
Altitude	
Mach	High subsonic (0.8)
Min. launch Mach	
Development	
Service	Foreseen: submunition version in 1997 with the French and German air forces and single warhead version in 2002 with French air force (Mirage 2000 and Rafale aircraft).
Boost motor	
Sustainer motor	Turbojet engine permitting subsonic speed at around Mach 0.8. Ref. [15]: Both versions of Apache derivates will use airframe and Microturbo engine used for the Apache-A runway interdiction missile.
Transition	
Intakes	
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

French programme (Refs. [32, 21])

Application	Matra/ONERA surface-to-air/air-to-ground development programme. Complete tactical missile fired recently (1995). It was a ground-to-air test with the flight profile of an air-to-air missile. Matra/ONERA have been working to develop the ramjet for around 10 years. Also test flight for air-to-ground related system foreseen in 1995. Most likely near-term application: French future Anti-Radar (ARF) programme and Anti-AWACS air-to-air missile. First real application: replace Matra Martel and Armat weapons. **(Rustique programme ?)**
Length	
Max. body diameter	
Fin span	
Guidance	
Weight	About 150 kg.
Range	About 50 km at low altitude and much higher at high altitude engagements.
Altitude	
Mach	> 2
Min. launch Mach	
Development	Ref. [21]: full-scale development would be realized around 1998/1999 and is expected to become an international programme with Germany showing strong interest. Production in France by Matra and Celerg.
Service	
Boost motor	Solid propellant rocket motor, integrated in ramjet combustor
Sustainer motor	Integral rocket ramjet, unchoked. Gas generator propellant adapts to ramjet combustor pressure (self-adapting). Pay-off of self-regulating IRR design is lighter-weight/lower-cost rocket-ramjet with extremely rapid acceleration.
Transition	Ejectable port covers.
Intakes	
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

CASOM, Conventionally Armed Stand-Off Missile (Refs. [22, 15])

Application	Long-range precision weapon, attack of strategic and tactical targets, a capability that proved useful to Desert Storm allies during the Gulf conflict. Missile on RAF's Tornado, Harrier and Eurofighter 2000 aircraft. Ref. [15]: CASOM requirements are similar to those for anti-infrastructure Apache.
Length	
Max. body diameter	
Fin span	
Guidance	
Weight	
Range	
Altitude	
Mach	
Min. launch Mach	
Development	
Service	In-service date around the turn of the century.
Boost motor	
Sustainer motor	
Transition	
Intakes	
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	

SS-N-26 'Yakhont' (Refs. [39,14,24])

Application	3K55 Yakhont (SS-N-26). Anti-ship missile. Experimental motor, suitable for propulsion of a missile showed during 1994 Moscow salon. Intention of Plamya (constructor of the motor) to cooperate with Aerospatiale, which develops the motors for the ASMP and the Anti-Ship ANS. Ref. [14]: new vertical-launched anti-ship missile for naval craft. Integral rocket/ramjet. Ref. [24]: Yakhont future project, being now developed by NPO Mash (?).
Length	Ref. [14]: 8473 mm
Max. body diameter	800 mm, Ref. [14]: 762 mm
Fin span	Ref. [14]: 1402 mm
Guidance	Ref. [14]: inertial/active radar
Weight	Weight of motor 200 kg, Ref. [14]: total launch weight: 2270 kg
Range	Ref. [14]: 250 km
Altitude	
Mach	2 - 3.5 (at 20 km flight)
Min. launch Mach	
Development	
Service	
Boost motor	
Sustainer motor	Liquid fuel ramjet. Fuel is pumped at a fuel pressure of 220 bar.
Transition	
Intakes	
Fuel	
Flame stabilizer	
Combustor	
Fuel injection	
Liner	Thermal protection at the back of the motor.

S225X(R) (Refs. [19, 8, 20])

Challenge to the US AIM-120 AMRAAM. BAe, Saab, Alenia, GEC-Marconi. Aim: 40% improvement over the AIM-120 in overall kinematic performance at roughly the same market price. Prevent global AMRAAM monopoly. Industrial consortium hopes to provide choice for equipping both Eurofighter 2000 and Gripen as well as an export weapon. (S for stealth, X for experimental). Ref. [20]: Same body as BAe's Active Sky Flash, but without mid-body control fins and instead of the rear wings, four tail control fins fitted. Missile compatible with Sky Flash and AIM-7 Sparrow launching systems and employs digital interface for ease of aircraft integration. In 1994, four-company consortium (BAe, GEC-Marconi, Saab Missiles and Alenia) propose ramjet-powered S225XR missile as a future medium-range AAM.

Application	Future European medium/long-range (BVR) AAM.
Length	
Max. body diameter	
Fin span	
Guidance	Active radar seeker or dual-mode multispectral seekers. Features to defeat EW environment. Ref. [20]: Stealth mainly through low power output from active radar seeker and through a low infra-red thermal signature from the motor. Datalink for long-range engagements, which would be around 50 km. Initially active radar seeker but dual mode active radar/IR seeker is later option.
Weight	
Range	> 100 km. Ref. [20]: S225XR design is aimed at achieving a maximum range of around 100 km.
Altitude	
Mach	
Min. launch Mach	
Development	Start BAe/Saab in June 1992. Missile offered to Sweden as RB 91.
Service	
Boost motor	Solid propellant, BAe: long-range AAM possibly with double-boost motor in the rear. The missile itself would decide on the best engagement options and would select when to light the second booster.
Sustainer motor	Ref. [19]: If S225XR project goes ahead, then possibly with a French ramjet motor because nowhere else is ramjet technology far enough ==> typical development time for an engine is 8-10 years from concept to production.
Transition	
Intakes	

EFA, experimental missile (Ref. [6])

Application	EFA flight tests carried out by MBB, Germany, in 1982.
Length	4.2 m
Max. body diameter	240 mm
Fin span	
Guidance	
Weight	
Range	One ballistic and one guided test flight: altitude approximately 1500 m, Mach 2.5, high g-side manoeuvres during second flight.
Altitude	
Mach	
Min. launch Mach	
Development	
Service	
Boost motor	Tandem boost, ground launched (test vehicle)
Sustainer motor	End burning gas generator grain, high energy propellant (40% boron-loaded), fixed flow.
Transition	
Intakes	Four lateral half-axisymmetric air intakes
Fuel	
Flame stabilizer	
Combustor	Side dump ram-combustor
Fuel injection	Fixed flow
Liner	

A3M, Daimler-Benz Aerospace (DASA) study (Konzept-Vorschlag, Refs. [18, 9])

Application	Advanced Air-to-Air Missile (A3M) for Eurofighter 2000. Can be fitted to all AMRAAM designed Eject-Launch and Ral-Launch stations of Eurofighter. Wolfram-Heavy metal blast/splitter warhead. UK requirements for FMRAAM: 'Staff Requirement 1239'.
Length	3655 mm
Max. body diameter	180 mm
Fin span	
Guidance	K_a band radar, X-band receiver (8-13 GHz) for passive discovery of target position and 'home-on-jam' possibility. Inertial faser (fibre ?)-optic Kreiseln (?) to enhance navigation precision at high speeds.
Weight	165 kg
Range	Ref. [9]: capable of >250 km at high altitude with large growth potential.
Altitude	
Mach	High supersonic Mach number ==> bank-to-turn mode and switched to skid-to-turn mode 2 seconds before hit of target.
Min. launch Mach	Launch at Mach 0.9 at an altitude of 3000 m
Development	Now.
Service	Foreseen for EF2000 and JAS39 GRIPEN ==> first decade next century ?
Boost motor	Solid rocket, boost phase during 2.3 seconds
Sustainer motor	Ducted rocket with boron propellant to attain high volumetric heating value.
Transition	Boost during 2.3 seconds to Mach 2.3 at 1200 m from launch platform
Intakes	Figures Refs. [18,9] suggest two 2-D aft-belly inlets (under body). Bank-to-turn steering until last few seconds to target, then switch over to skid-to-turn mode.
Fuel	Gas generator boron-loaded Bayern-Chemie development. About 10% oxidizer.
Flame stabilizer	
Combustor	
Fuel injection	Gas generator valve. TDR capability shown 1:9; requirement for A3M is only 1:6 ==> flexibility to missions.
Liner	

ONGERUBRICEERD

REPORT DOCUMENTATION PAGE
(MOD-NL)

1. DEFENCE REPORT NO. (MOD-NL)	2. RECIPIENT'S ACCESSION NO.	3. PERFORMING ORGANIZATION REPORT NO.
TD96-0427		PML 1996-A100
4. PROJECT/TASK/WORK UNIT NO.	**5. CONTRACT NO.**	**6. REPORT DATE**
223496300	A95KLu487	December 1996
7. NUMBER OF PAGES	**8. NUMBER OF REFERENCES**	**9. TYPE OF REPORT AND DATES COVERED**
77 (incl. 2 annexes, excl. RDP & distribution list)	39	Final

10. TITLE AND SUBTITLE

Developments in missile ramjet propulsion

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14. SUPPLEMENTARY NOTES

The classification designation Ongerubriceerd is equivalent to Unclassified.

15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

At the request of the Royal Netherlands Air Force, a study into the international developments on missile ramjet propulsion has been carried out. It is the objective of this work to provide an outline of ramjet propulsion for missiles with a view on technical and operational aspects as well as the ongoing international developments. The essential areas for employment of missile systems, which are presently insufficiently perceived for ramjet missile systems, have been identified in accordance with the Royal Netherlands Air Force. Future work on these areas will be defined in consensus with the Royal Netherlands Air Force.

16. DESCRIPTORS	IDENTIFIERS
Ramjet propulsion Missiles	

17a. SECURITY CLASSIFICATION (OF REPORT)	17b. SECURITY CLASSIFICATION (OF PAGE)	17c. SECURITY CLASSIFICATION (OF ABSTRACT)
Ongerubriceerd	Ongerubriceerd	Ongerubriceerd
18. DISTRIBUTION AVAILABILITY STATEMENT		**17d. SECURITY CLASSIFICATION (OF TITLES)**
Unlimited Distribution		Ongerubriceerd

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3 DWOO

4* HWO-KL

5 HWO-KLu

6* HWO-KM

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